NPS-67-84-008

# NAVAL POSTGRADUATE SCHOOL

## Monterey, California

# THESIS

GROUND-UP-TO-SPACE (GUTS)
LASER PROPGATION CODE
DESCRIPTION AND MANUAL

by

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June 1984

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Prepared for: Dr. Fred Raymond, Code 9110
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This thesis prepared in conjunction with research supported in part by the Naval Research Laboratory, Washington, D.C.



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## REPORT DOCUMENTATION PAGE

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| | | |
|---|---|---|
| 1. REPORT NUMBER<br>NPS 67-84-008 | 2. GOVT ACCESSION NO. | 3. RECIPIENT'S CATALOG NUMBER |
| 4. TITLE (and Subtitle)<br>Ground-Up-to-Space (GUTS) Laser Propagation Code Description and Manual | | 5. TYPE OF REPORT & PERIOD COVERED<br>Master's Thesis<br>June 1984 |
| | | 6. PERFORMING ORG. REPORT NUMBER |
| 7. AUTHOR(s)<br>Joel Steven Morrow | | 8. CONTRACT OR GRANT NUMBER(s)<br>N0001484WRP4012 |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS<br>Naval Postgraduate School<br>Monterey, California, 93943 | | 10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS |
| 11. CONTROLLING OFFICE NAME AND ADDRESS<br>Naval Postgraduate School<br>Monterey, California, 93943 | | 12. REPORT DATE<br>June 1984 |
| | | 13. NUMBER OF PAGES<br>141 |
| 14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)<br>Dr. Fred Raymond<br>Naval Research Laboratory<br>4555 Overlook Ave. SW<br>Washington, D.C. 20375 | | 15. SECURITY CLASS. (of this report)<br>Unclassified |
| | | 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE |

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

High Energy Laser
Laser Propagation
Laser Weapon Simulation Program
ASAT Laser Simulation

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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# Ground-Up-to-Space (GUTS)
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# Description and Manual

by

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN AERONAUTICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
June 1984

# ABSTRACT

GUTSAVG is a high energy laser propagation computer program for ground-to-space applications. Written by Dr. C. E. Hogge from the Air Force Weapons Laboratory, Kirtland AFB, it is one in a family of propagation codes addressing this application. Specifically, GUTSAVG was designed to compute irradiance at the target given a model atmosphere, laser device parameters, and simple target engagement geometry. The transmitter induced effects of beam quality and jitter are considered as are the linear atmospheric effects of scattering, absorption, and turbulence. A thermal blooming model is also included. Adaptive optics compensation can be applied with consideration given to isoplanatic effects.

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## I. INTRODUCTION

GUTSAVG is a simplified laser propagation program. It is intended specifically for near vertical ground-to-space applications utilizing a fixed earth-based transmitter directed at a single target satellite. The primary purpose of the program is to provide irradiance and fluence on target along with related propagation data.

The program was written by Charles B. Hogge from the Air Force Weapons Laboratory, Kirtland Air Force Base, Albuquerque, New Mexico. GUTSAVG is one of a family of ground-to-space propagation programs. Other versions include GUTSFP (footprint) and GUTSMTF. GUTSFP computes an engagement envelope based on user supplied irradiance threshold levels. The propagation calculation methods are identical to GUTSAVG. GUTSMTF is a full wave-optics program using fast Fourier transforms in the beam propagation computations.

The basic approach used in GUTSAVG is to utilize modulation transfer functions to characterize effects such as beam quality, jitter, turbulence and to apply these effects at the aperture as a single phase screen. The same approach is used in ESP-IV [Ref. 1]. The general modulation transfer function, (MTF), used in this way is described in following sections along with the development of each beam degrading mechanism. A linearized model is used for thermal blooming which is also effectively applied at the aperture as a phase screen. In the case of blooming, however, the phase variance due to blooming is computed, and the Strehl relation is used to determine the relative irradiance reduction. The effect of thermal blooming and the other spreading effects are combined using both RSS and multiplicative methods. Finally, the average of these two methods is used to determine the

total system irradiance reduction from the diffraction limited case.

# II. PROPAGATION FEATURES

## A. THE MTF APPROACH

GLTSAVG uses MTFs to apply and then to consolidate the effects of jitter, beam quality, and turbulence. Essentially, these effects are replaced by a phase screen at the aperture which multiplies the initial complex aperture distribution by a random phase distortion factor.

Lutomirski and Yura [Ref. 2] have developed an expression for the average intensity at a point P in the far-field due to perturbations at the aperture. The intensity at P is

$$I(\overline{p}) = \left(\frac{k}{2\pi z}\right)^2 \int M_\phi(\overline{\rho}, z) \exp\left[-\left(\frac{i \cdot k}{z}\right)\overline{p}\,\overline{\rho}\right] d^2\overline{\rho} + \int U(r+\tfrac{1}{2}\overline{\rho})\, U^*(r-\tfrac{1}{2}\overline{\rho}) \exp\left[-\left(\frac{i \cdot k}{z}\right) r\overline{\rho}\right] d^2 r \tag{2.1}$$

where

$$\overline{\rho} = |r_2 - r_1| \tag{2.2}$$

and

$$r = \frac{r_2 + r_1}{2} \tag{2.3}$$

$\overline{p}$ is the vector from the z axis of symmetry in the far-field to the point P. U(r) is the aperture distribution and $M_\phi(\overline{\rho}, z)$ is the MTF for the disturbance. $r_1$ and $r_2$ are two arbitrary points in the aperture where the phase perturbation is measured. $\overline{\rho}$ is the distance between the points. z, in the

case considered here, is a constant. If the phase disturbance is a random Gaussian variable with a known correlation function, then the MTF can be expressed as

$$M_{\phi}(\bar{\rho}) = \langle \exp[i(r_1 - r_2)] \rangle \tag{2.4}$$

In terms of the structure function,

$$M_{\phi}(\bar{\rho}) = \exp\left[(-\tfrac{1}{2}) D_{\phi}(r_1 - r_2)\right] \tag{2.5}$$

The second integral in equation 2.1 represents the unnormalized aperture MTF. Normalizing this term with the power in the aperture, $(P_0)$, to cause the MTF to be unity at the origin results in

$$I(\bar{p}) = \left(\frac{k}{2\pi z}\right)^2 P_0 \int M_{\phi}(\bar{\rho}) M_a(\bar{\rho}) e^{-[ik\bar{\rho}\bar{p}]} d\bar{\rho}^2 \tag{2.6}$$

Noting the symmetry of the intensity for a given p and expressing $M_{\phi}(\rho)$ as the combined effects of jitter, beam quality, and turbulence, equation 2.6 can be rewritten as

$$I(\bar{p}) = \left(\frac{k}{2\pi z}\right) P_0 \int M_j(\bar{\rho}) M_t(\bar{\rho}) M_b(\bar{\rho}) M_a(\bar{\rho}) J_0\left(\frac{k\bar{\rho}\bar{p}}{z}\right) \bar{\rho} d\bar{\rho} \tag{2.7}$$

A Fourier-Bessel transform has been used. Note that the MTFs of jitter $(M_j)$, beam quality $(M_b)$, and turbulence $(M_t)$ have been substituted for $M_{\phi}$.

The ESP-IV manual [Ref. 3] contains the development above in more detail. MTFs for the specific effects are described in following sections.

## E. THERMAL BLOOMING

The thermal blooming model in GUTSAVG is based on the following linearized density perturbation equation.

$$\frac{\Delta\rho}{\rho_0} = \frac{\alpha(\ell)}{V_0}\,\frac{\gamma-1}{\gamma}\,\frac{1}{p_0}\int_{-\infty}^{x'} I(x',y)\,dx' \qquad (2.8)$$

$$\times \exp\left[-\int\left[\alpha(\ell)+\sigma(\ell)\right]d\ell\right]$$

Here, $\alpha(\ell)$ is the atmospheric absorption coefficient at a distance $\ell$ along the beam, $V_0$ is a constant transverse wind velocity, and $p_0$ is the ambient pressure. The exponential term represents the total extinction due to scattering and absorption. $x'$is a constant of integration. It is assumed that the beam is propagated in the positive z direction a distance $\ell$ and that the wind vector is in the positive x direction. The intensity integral represents the heating of the atmosphere as it transits the beam [Ref. 4]. Some assumptions embodied in the above equation are that $V_0 << c_0$ , the local sonic velocity, so that the process represented occurs at constant pressure, and that the kinetics of absorption and conversion to heat are extremely fast [Ref. 5].

By applying the Gladstone-Dale relation,the density relation can be expressed as a change in the refractive index.

$$\Delta n = (n_0-1)\frac{\Delta\rho}{\rho_0} \qquad (2.9)$$

Equation 2.8 can be rewritten as

$$\Delta n = (n_0-1)\frac{\alpha(\ell)}{V_0}\,\frac{\gamma-1}{\gamma}\,\frac{1}{p_0}\int_{\infty}^{x'} I(x',y)\,dx' \times \exp\left[-\int[\alpha(\ell)+\sigma(\ell)]\,d\ell\right] \tag{2.10}$$

The change in the wavefront phase of a beam due to the refractive index charge when the beam is propagated a distance $\ell$, is given by

$$\Delta\phi = \frac{2\pi}{\lambda}\int_0^{\ell}\Delta n\,d\ell \tag{2.11}$$

Substituting equation 2.10 into 2.11 and changing the limits of integration to reflect the ground-to-space propagation path results in

$$\Delta\phi(x,y) = \left[\frac{2\pi}{\lambda}\,\frac{n_0-1}{p_0}\,\frac{\gamma-1}{\gamma}\int_{-\infty}^{x'} I(x',y)\,dx'\right] \times \int_{h_t}^{h_{atm}} \frac{\alpha(h)\exp\left[-\sec\theta\int_{h_t}^{h}[\alpha(h)+\sigma(h)]\,dh\right]}{V_0\cos\xi + \omega h}\,dh \tag{2.12}$$

$h_{atm}$ is the extent of the atmosphere, which is about about 30 km, and $h_t$ is the height of the laser transmitter. Also, the wind term has been expanded to include the relative wind velocity due to slewing. $V_0$ is assumed to be parallel and opposite in direction of that of the target motion. $\xi$ is the angle of incidence of the wind to the beam so that $V_0\cos(\xi)$ represents the transverse wind. $\omega h$ is the effective wind generated by slewing. $\omega$ is the angular slew rate.

The first portion of equation 2.12 is independent of path while the second part is not, assuming I(x,y) does not change along the propagation path. This assumption is valid only for a very small amount of blooming. The approach used

in GUTSAVG is to determine the phase distortion due to thermal blooming by first evaluating the path invariant part of equation 2.12 . This is accomplished by constructing a phase screen at the aperture and then removing the best fit tilt, focus curvature, and mean phase. Zernike polynomials are used to model these aberrations. The result is the residual phase due to thermal blooming alone. The variance of the phase is then computed.

The path dependent term is evaluated within the angle interval loop of the program and is applied to the previously computed phase variance during each path iteration. The path iteration process is diagrammed in the engagement geometry section. Also, see Figures 2.1 and 2.2 for a flow diagram of the general treatment of thermal blooming in the program.

Once the total phase variance has been determined, the Strehl relation is used to compute the intensity degradation due to thermal blooming.

$$\frac{I}{I_0} = \exp(-\sigma^2) \tag{2.13}$$

The result of equation 2.13 is a relative intensity (Irel) ratio. $I_0$ is the ideal on-axis irradiance with no phase distortion. The Strehl relation above is thought to be too severe a model for Irel below 0.3 [Ref. 6]. For that reason, if $\sigma^2$ is less than 1.2 , the Irel will be computed using polynomial curve fits developed from GUTSMTF results. GUTSMTF is a full wave optics code utilizing fast Fourier transforms. For a description of the curve fit method above, see the subroutine BLOOM explanation. [Ref. 7]

Combining the thermal blooming effect with the other effects, such as turbulence and jitter, is accomplished by averaging the results of two different approaches. The first

approach is the RSS (root sum squared) method. This method of combining the Irel due to the effects of thermal blooming with the Irel due to jitter, beam quality, and turbulence is accomplished as follows

$$\mathrm{Irel}_{rss} = \left(1+\left[\frac{1}{\mathrm{Irel}_{tb}}-1\right] + \left[\frac{1}{\mathrm{Irel}_{o}} - 1\right]\right)^{-1} \qquad (2.14)$$

where $\mathrm{Irel}_{tb}$ is the thermal blooming result and $\mathrm{Irel}_o$ is the result of the other effects. The second approach is a multiplicative approach and is simply

$$\mathrm{Irel}_m = \mathrm{Irel}_o \times \mathrm{Irel}_{tb} \qquad (2.15)$$

The two combined Irels obtained by these methods are then averaged to give the total intensity ratio due to all the attenuating or distorting propagation effects.

$$\frac{I}{I_0} = \mathrm{Irel}_{tot} = \frac{\mathrm{Irel}_m + \mathrm{Irel}_{rss}}{2} \qquad (2.16)$$

$I_0$ is the ideal diffraction limited on-axis intensity. The bases for the above averaging process is empirical in nature and is an attempt to adjust the results obtained by the RSS method alone. The results produced by RSS were thought to be too optimistic. The multiplicative method, a more pessimistic approach, was therefore included. The ultimate Irels obtained are very close to those obtained by GUTSMTF, the full wave code. [Ref. 8]

There are some limitations to the thermal blooming model used in GUTSAVG in addition to the assumptions already mentioned. First, the wind ($V_0$) is applied as a constant

everywhere in the atmosphere. At higher altitudes, this is not a major consideration due to the higher relative velocity of the beam. At low to medium altitudes this could affect thermal blooming to an extent to warrant the addition of a wind profile as a function of altitude. This could be done with little effort if the data is available. Also, the program assumes a wind parallel and opposite to the direction of the target motion. This precludes the case of slewing with the wind and the creation of null spots. Transonic blooming, which violates one of the original assumptions of the equation used, is not considered [Ref. 9]. For very low altitude satellites, the high slew rates generated would result in a supersonic relative wind across the beam. In this case, the constant pressure assumption is invalid [Ref. 10]. Kinetic cooling and molecular breakdown are also not addressed in GUTSAVG.

## C. SCATTERING AND ABSORPTION

GUTSAVG does not contain any type of atmospheric model with respect to scattering and absorption data. Extinction coefficients must be entered by the user in the appropriate subroutines, ALFS and ALFA, or the program can be modified to accept a separate data file. Once inserted into the program, scattering and absorption coefficients are treated without distinction between aerosol and molecular mechanisms. Therefore, the coefficients used must represent the total effect of scattering or absorption.

$$\alpha(h) = \alpha(h)_{mol} + \alpha(h)_{aer} \qquad (2.17)$$

$$\sigma(h) = \sigma(h)_{mol} + \sigma(h)_{aer} \tag{2.18}$$

Transmission due to scattering and absorption are computed indentically and given by

$$T_a = \exp\left(-\sec\theta \int_{h_t}^{h_{atm}} \alpha(h)\,dh\right) \tag{2.19}$$

where $\theta$ is the zenith angle, and the integration limits are the altitude of the transmitter and the vertical extent of the atmosphere. The extent of the atmosphere in the program is defined as 30 km. Figure 2.3 shows the program application of scattering and absorption.

## D. BEAM QUALITY

GUTSAVG allows the user to describe the beam at the aperture in terms of the electromagnetic field amplitude distribution and total beam quality. The intital amplitude field used by the program is Gaussian in shape with the user specifying a waist diameter. The waist diameter is defined by the $1/e^2$ point on the distribution. Truncation of the this Gaussian field will of course depend on the aperture diameter and the size of the central obscuration. If the waist diameter is made large compared to the aperture, a more uniform distribution results.

Beam quality at the aperture exit may be specified by two different parameters. One of these is the 'times diffraction limited number', N. N has been used in a general way to mean an increase in far-field spot size or as a 'power-in-the-bucket' ratio. In GUTAVG, N is a total beam quality term. The second beam quality parameter is a nondimensional term representing the RMS phase distortion at the laser wavelength at the exit aperture, $\frac{\delta_{rms}}{\lambda}$.

The parameters are related to each other and to the intensity degradation by

$$\frac{I}{I_0} = \frac{1}{N^2} = \exp -\left(\frac{2\pi\delta_{rms}}{\lambda}\right)^2 \qquad (2.20)$$

To apply beam quality to the propagation problem, an MTF array is constructed representing a phase screen at the aperture. The phase is assumed to be a Gaussian random variable with a zero mean value. For the axi-symmetric beam considered in GUIAVG, the MTF is [Ref. 11]

$$M_b(\bar{\rho}) = \exp\left(-k^2\left[\sigma^2 - C_\phi(\bar{\rho})\right]\right) \qquad (2.21)$$

$C_\phi$ is the autocorrelation function of the phase and is defined as

$$C_\phi(\bar{\rho}) = \sigma^2 \exp\left[-\left(\frac{\bar{\rho}}{L}\right)^2\right] \qquad (2.22)$$

where $\sigma^2$ is the phase variance, $\left(\frac{2\pi\delta_{rms}}{\lambda}\right)^2$, and L is the phase correlation length [Ref. 12]. The beam quality MTF array is combined with the MTF arrays due to other propagation effects to determine the complete system MTF and, hence, the total irradiance degradation. Based on the provided input parameter, Figure 2.4 shows the general treatment of beam quality within the program.

## E. TURBULENCE

GUISAVG uses the Hufnagel model [Ref. 13] for $C_n^2$ as an indicator of the optical effects of turbulence along the propagation path. $C_n^2$ is the refractive index structure constant and represents the refractive index in the

atmosphere as a function of turbulence induced density fluctuations. The model is an empirically derived vertical profile of $C_n^2$.

Fried [Ref. 14] has developed a parameter which is directly related to the behavior of a coherent beam in a turbulent medium. This term is called the effective coherence diameter, $r_0$. In the case of a laser transmiter, $r_0$ represents a physical limit to the transmitter diameter of a near diffraction-limited beam. For a transmitter diameter, D, larger than $r_0$, degradation of the beam by turbulence will occur. If D is smaller than $r_0$, then near diffraction-limited propagation will be achieved. Beam wander or pure tilt occurs for transmitter diameters approximately equal to $r_0$. Yura [Ref. 15] has defined a somewhat different but related term that can be thought of as a lateral coherence length, $\rho_0$. These two quantities are given by

$$r_0 = \left[\frac{2.19}{6.88} k^2 \sec\theta \int C_n^2(h)\ dh\right]^{-3/5} \tag{2.23}$$

and

$$\rho_0 = \left[1.45\ k^2 \sec\theta \int C_n^2(h)\ dh\right]^{-3/5} \tag{2.24}$$

so that

$$\rho_0 = \frac{r_0}{2.1} \tag{2.25}$$

where $k = \frac{2\pi}{\lambda}$, $\theta$ is the zenith angle, and the limits of integration are $h_{atm}$, the vertical extent of the atmosphere, and $h_t$, the height of the transmitter.

$\rho_0$ may be specified by the user as a program input or the program may be allowed to compute it based on equation 2.24 . The user may also input $\rho_0$ indirectly by specifying the 'seeing conditions' , a quantity used by astronomers to describe angular spread of a stellar point source (see input section and Figure 2.5). The program uses $\rho_0$ to compute the atmospheric MTF.

The MTF of the turbulent atmosphere is determined by developing the structure function of the turbulence. This development is demonstrated by Yura [Ref. 16]. The resulting MTF is given by

$$M_t(\bar{\rho}) = \exp\left[-\left(\frac{\bar{\rho}}{\rho_0}\right)^{3/5}\right] \qquad (2.26)$$

This MTF effectively applies the the effect of turbulence along the propagation path as a phase screen at the aperture.

## F. JITTER

Beam jitter is a user input and is specified by the variance of the angular excursions of the beam. Using the 2-sigma-p definition,

$$2\sigma_p = \sqrt{2(\sigma_x^2 + \sigma_y^2)} \qquad (2.27)$$

where $\sigma_x$ and $\sigma_y$ are the axial variances of the jittered beam center in the far-field. $\sigma_x$ and $\sigma_y$ are random variables with Gaussian distribution and in the symmetric case , as considered by GUTSAVG, $\sigma_x = \sigma_y$ . The resultant intensity distribution due to jitter will also be a Gaussian distribution with $(2\sigma_p)$ representing the spot radius defined at the $1/e^2$ point. In other words, 86.5% of the beam energy will reside within the radius $2\sigma_p$ . [Ref. 17]

Jitter can be shown to be a wavefront tilt at the aperture. Using this approach, a phase screen at the aperture can be used to characterize the effects of jitter and a jitter MTF developed. That MTF is given by

$$M_j(\overline{\rho}) = \exp\left[\frac{-k^2\overline{\rho}^2(2\sigma_p)^2}{8}\right] \tag{2.28}$$

Figure 2.6 is a general flow diagram for the treatment of jitter within the program.

## G. ADAPTIVE OPTICS

The ability to apply adaptive optics corrections to the propagation problem has been included in GUTSAVG. The user has several options with respect to the type and degree of compensation desired. The following general discussion and figure 2.8 provides the needed insight to the effects of selecting the adaptive optics options.

The major compensation mode provided by the program is invoked by selecting full zonal adaptive optics with consideration given to isoplanatic effects. When selected, this model results in the correction of beam degradation due to turbulence. This is accomplished by correcting turbulence induced tilt and then adjusting $\rho_0$ so as to produce a predetermined level of adaptive optics performance. This predetermined performance is as measured by the Strehl ratio given a residual phase variance determined by the adaptive optics sensor phase. Parameters determining the phase error are the response bandwidth of the adaptive optics system, the number of system actuaters, the reflected radiant intensity of the target, and the target-to-sensor transmission. The resultant $\rho_0$ found in this manner is then used to compute the atmospheric MTF. When this 'corrected' MTF is used to compute the far-field intensity, the result will represent an adaptive optics corrected value.

Without invoking full zonal adaptive optics, the user may apply a tilt-only correction for turbulence. In this case some or all of the tilt due to turbulence may be removed before computing the atmospheric MTF. The degree of tilt compensation is specified by the user.

As mentioned above, isoplanatic effects are included in the adaptive optics calculations. This is also an option, however, and isoplanatic calculations may be inhibited by the user. The effect considered is the limitation of the adaptive optics system given an isoplanatic angle smaller than the target lead angle. Fried [Ref. 18] provides a discussion of isoplanatism and development of the isoplanatic angle.

Although adaptive optics compensation for thermal blooming is not modeled in a strict sense, a thermal blooming correction factor can be applied. This factor is simply a fractional constant that multiplies the thermal blooming phase variance before the Strehl relation is used to compute the intensity degradation.

Refer to the input definitions and the subroutines involved with adaptive optics. In addition, refer to figure 2.7 for more explanation.

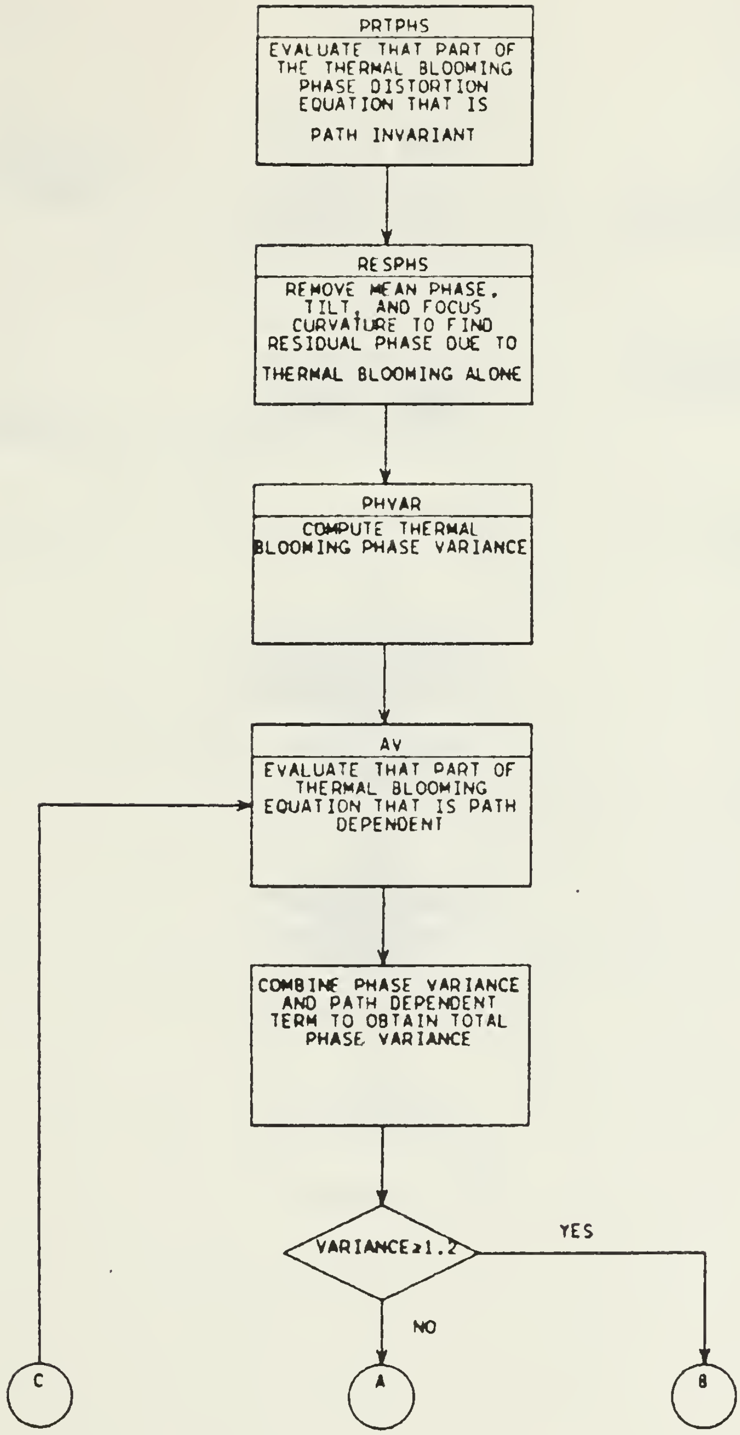


Figure 2.1 GLISAVG Thermal Blooming Algorithm.

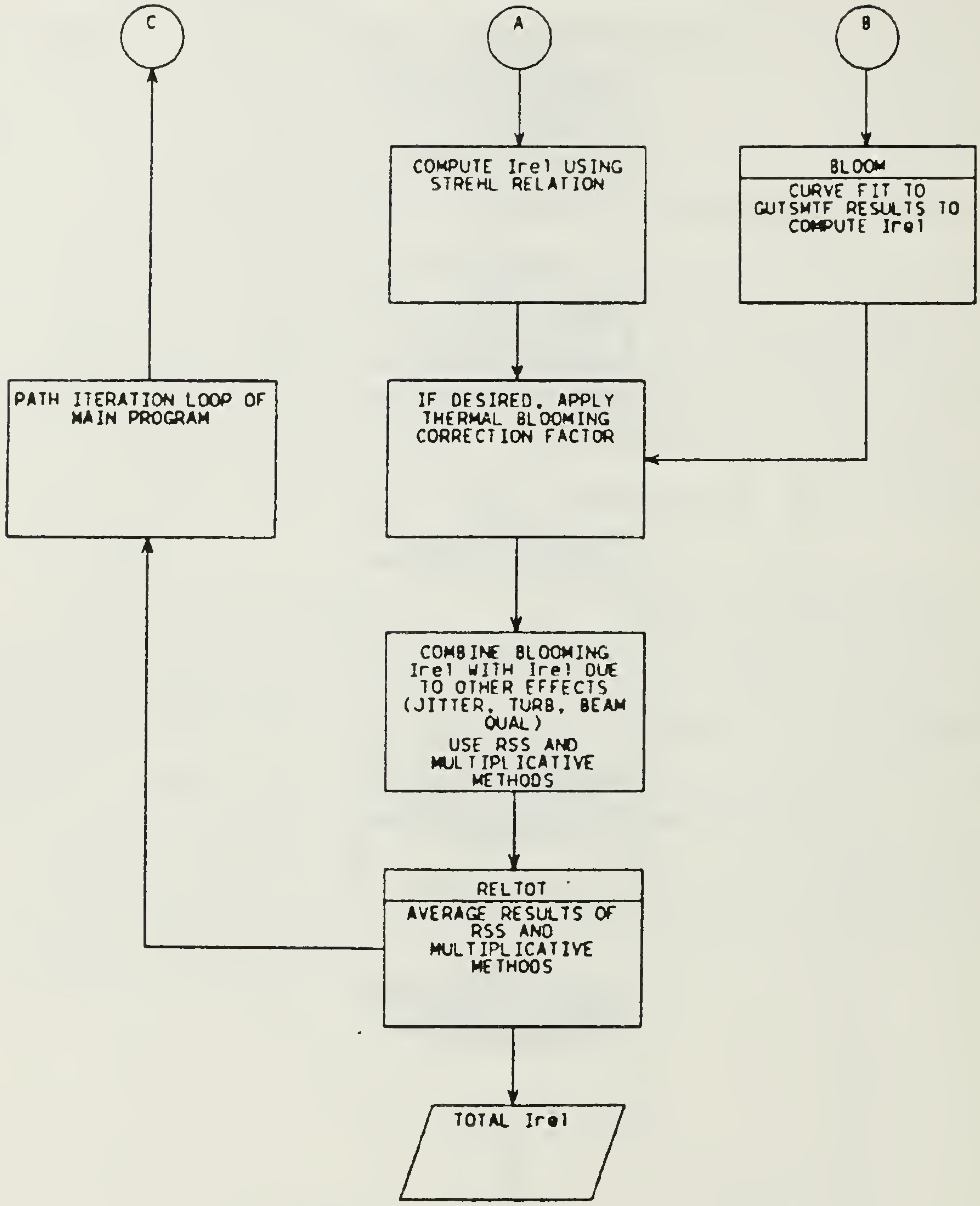


Figure 2.2 Thermal Blooming Algorithm (cont).

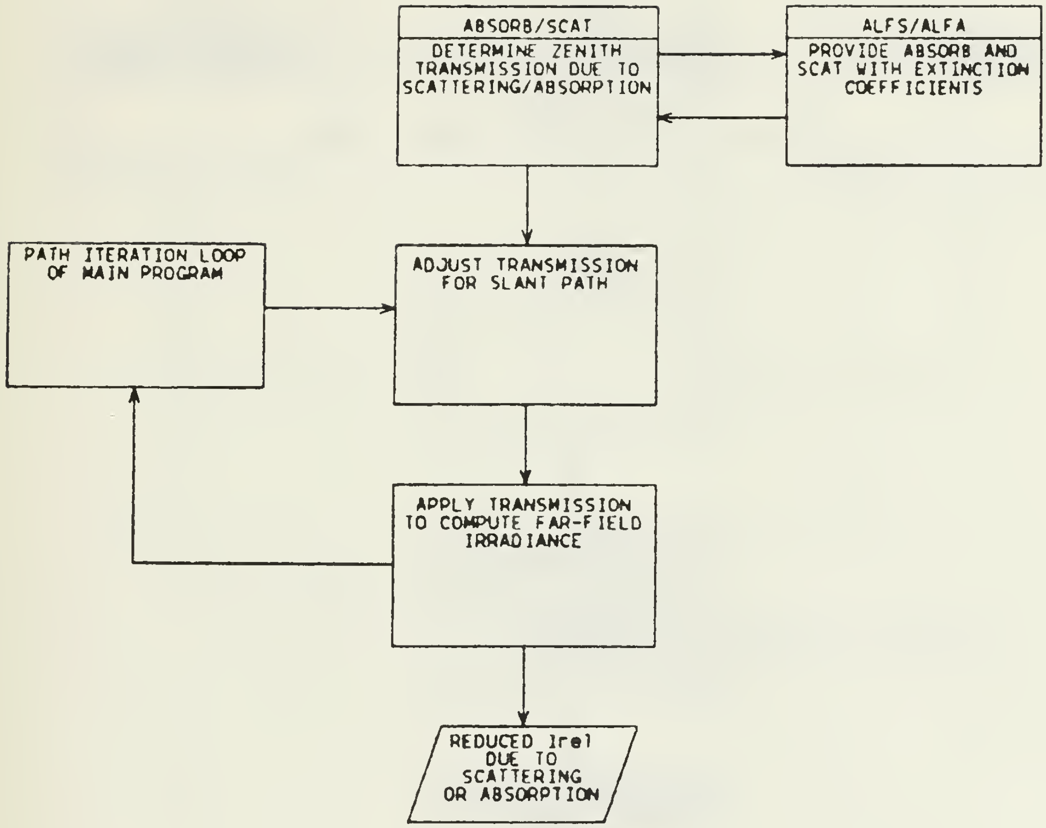


Figure 2.3 GUISAVG Scattering and Absorption Algorithm.

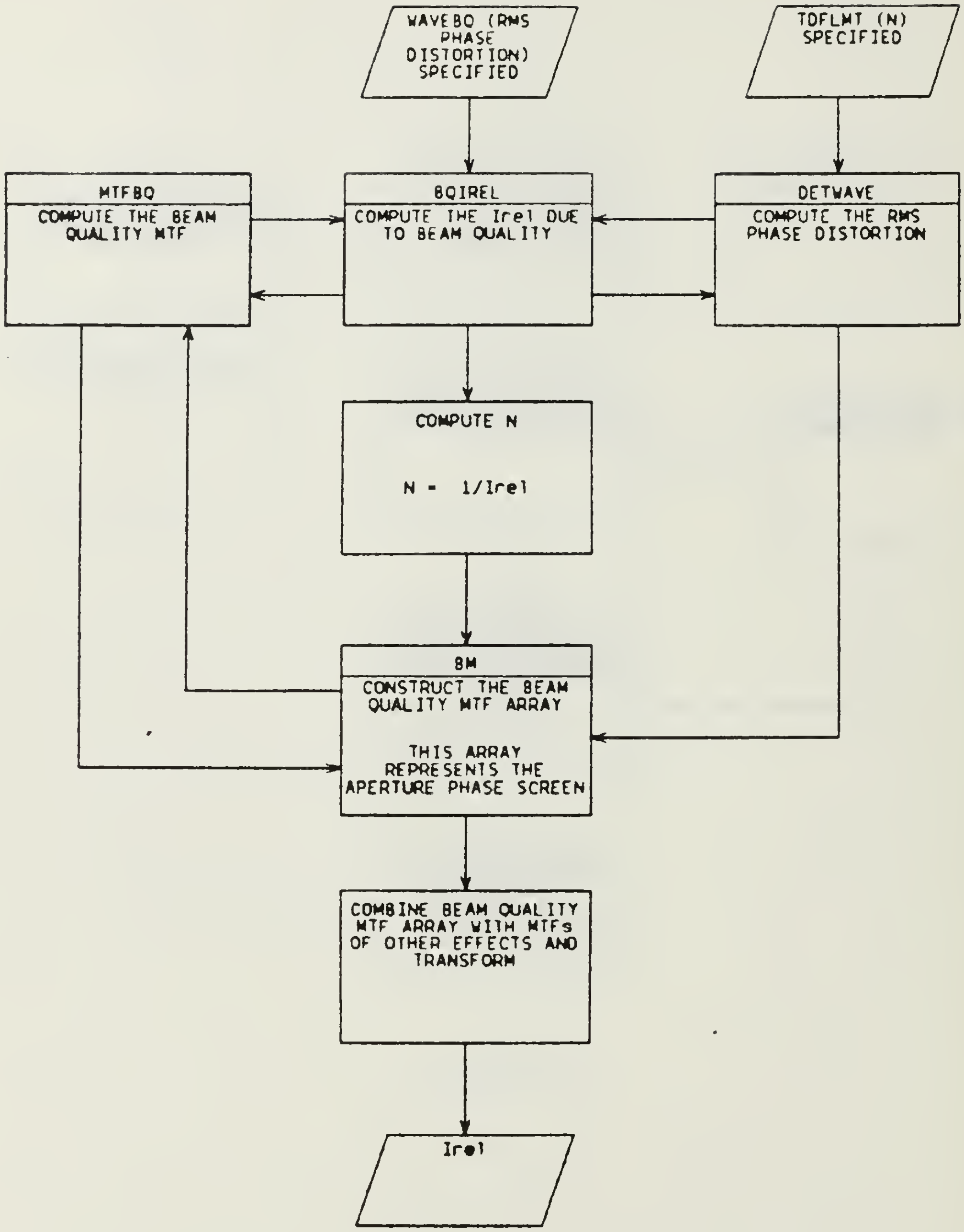


Figure 2.4 GUISAVG Beam Quality Algorithm.

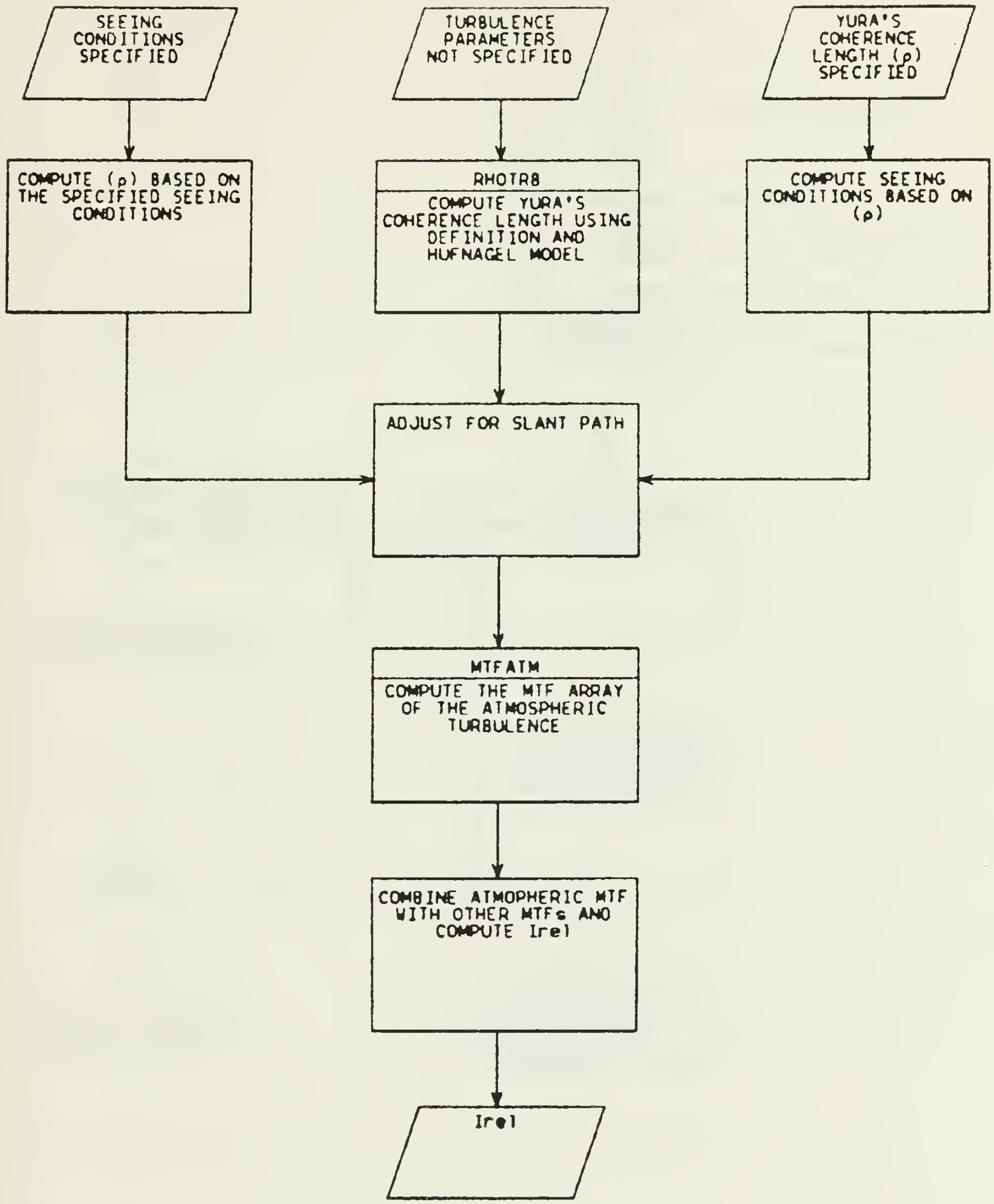


Figure 2.5 GUTSAVG Turbulence Algorithm.

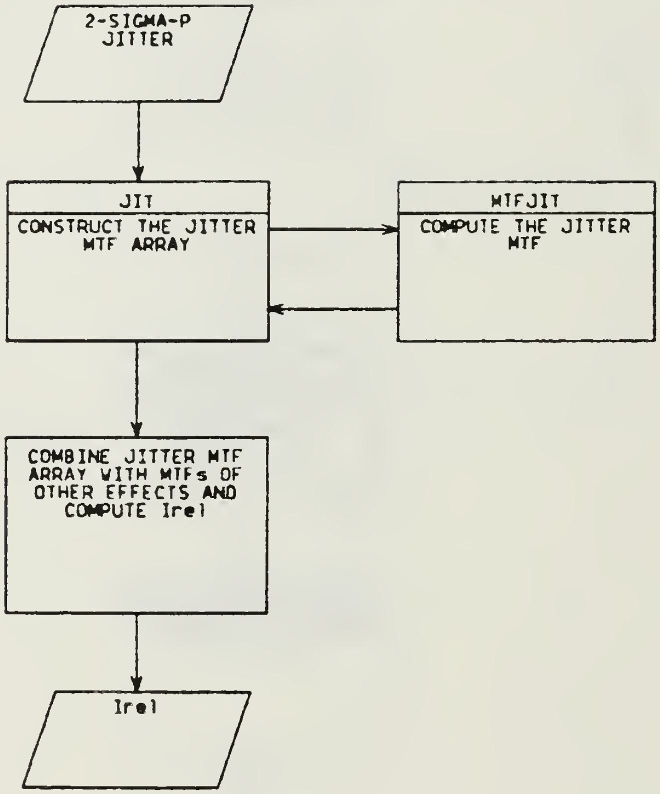


Figure 2.6 GUTSAVG Jitter Algorithm.

INPUT DECISIONS

| | |
|---|---|
| NFLAGA | FULL ZONAL AO |
| 1 | YES |
| 0 | NO |
| NOISO | INHIBIT ISOPLANATIC CALCULATIONS |
| 1 | YES |
| 0 | NO |
| ADAP | RESIDUAL TURBULENCE TILT |
| 0.0 | REMOVE 100% OF THE TURBULENCE TILT |
| 1.0 | REMOVE 0% OF THE TURBULENCE TILT |
| AOBLOM | THERMAL BLOOMING CORRECTION |
| 0.0 | REMOVE 100% OF THE THERMAL BLOOMING |
| 1.0 | REMOVE 0% OF THE THERMAL BLOOMING |

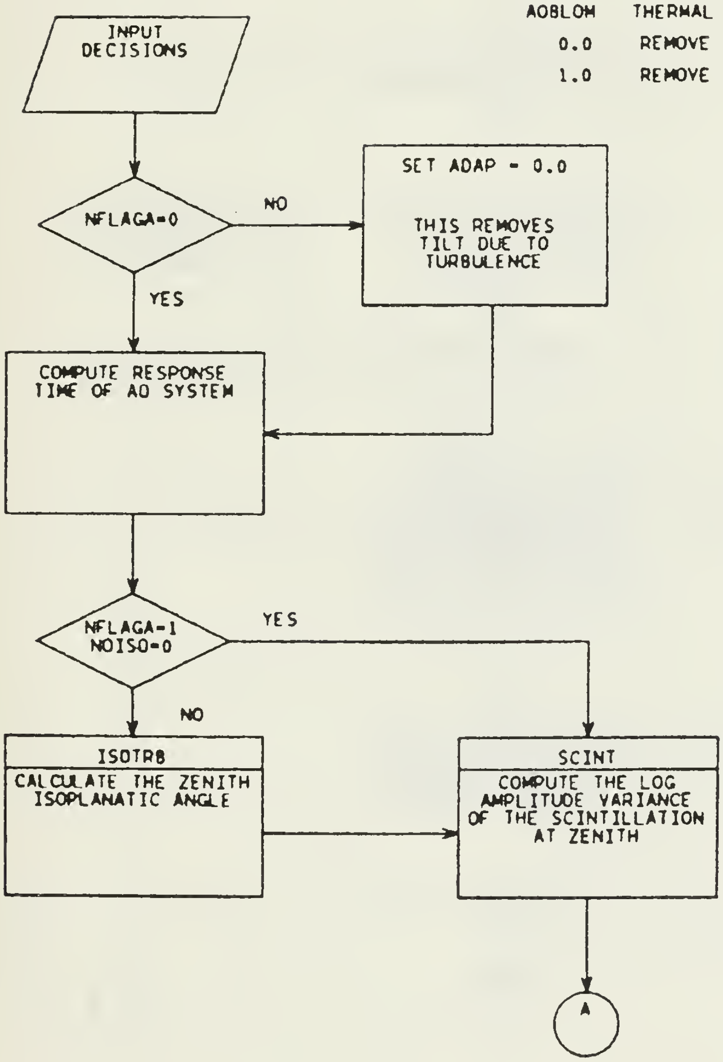


Figure 2.7 GLISAVG Adaptive optics Algorithm.

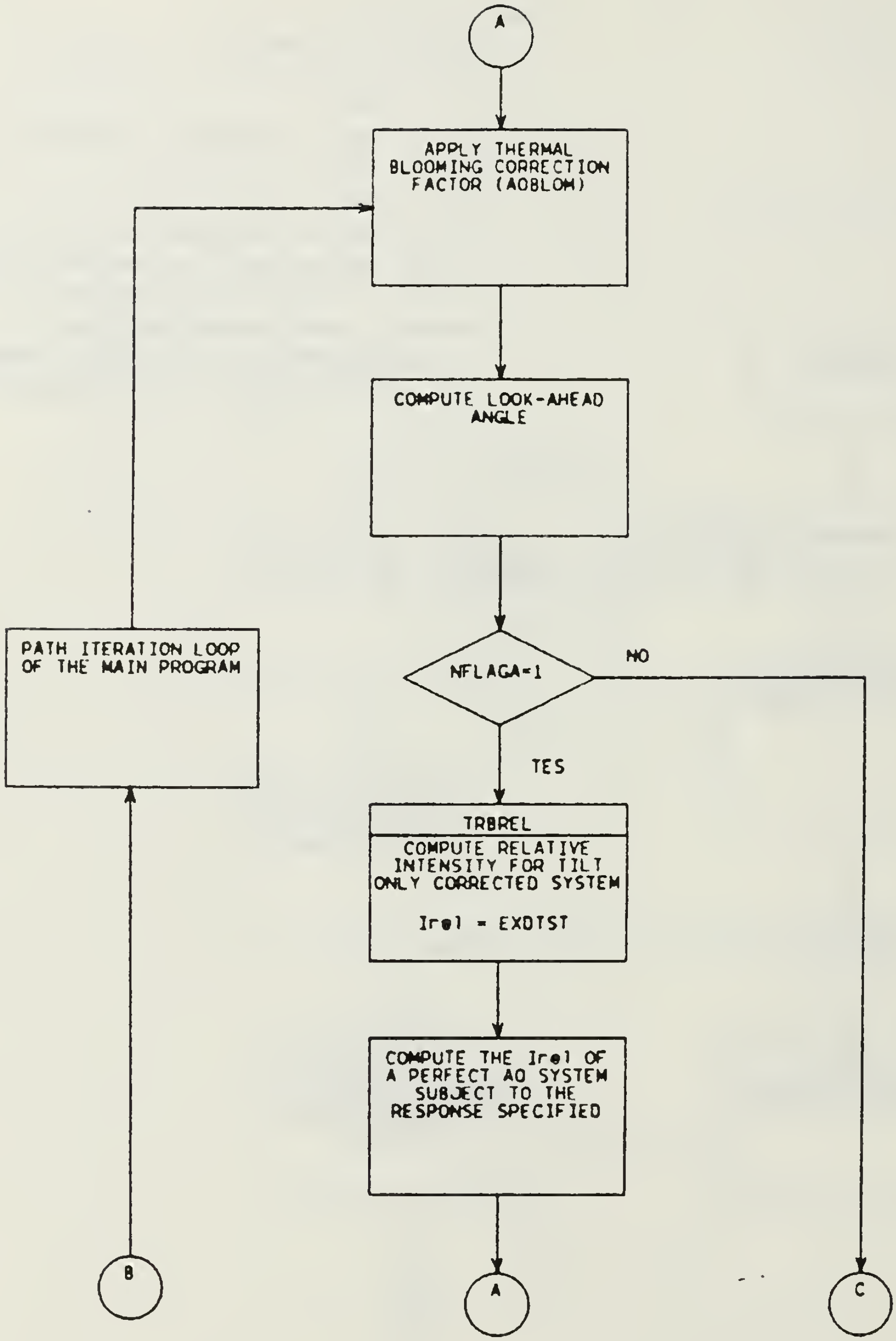


Figure 2.8 GUTSAVG Adaptive Optics Algorithm (cont).

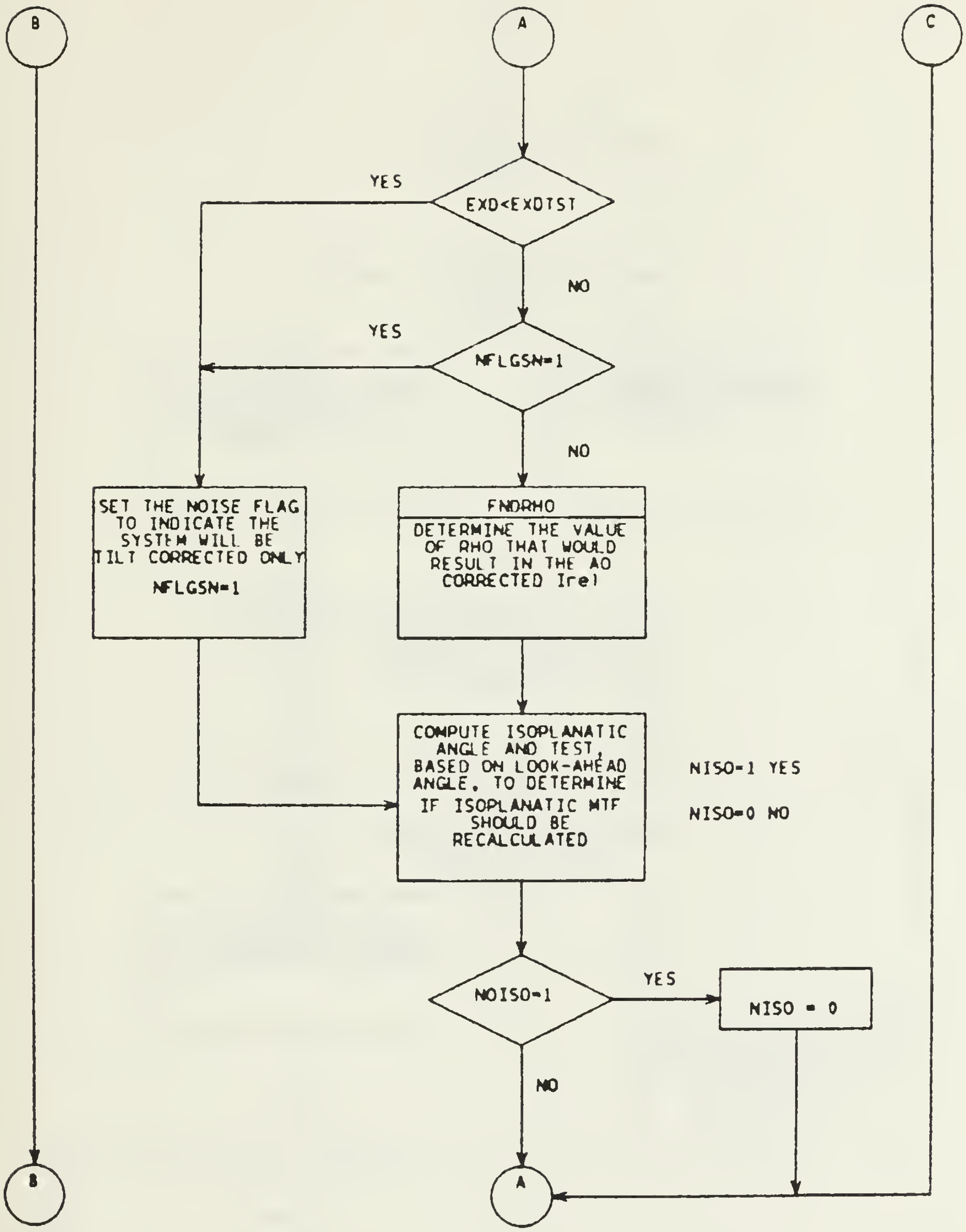


Figure 2.9 GUTSAVG Adaptive Optics Algorithm (cont).

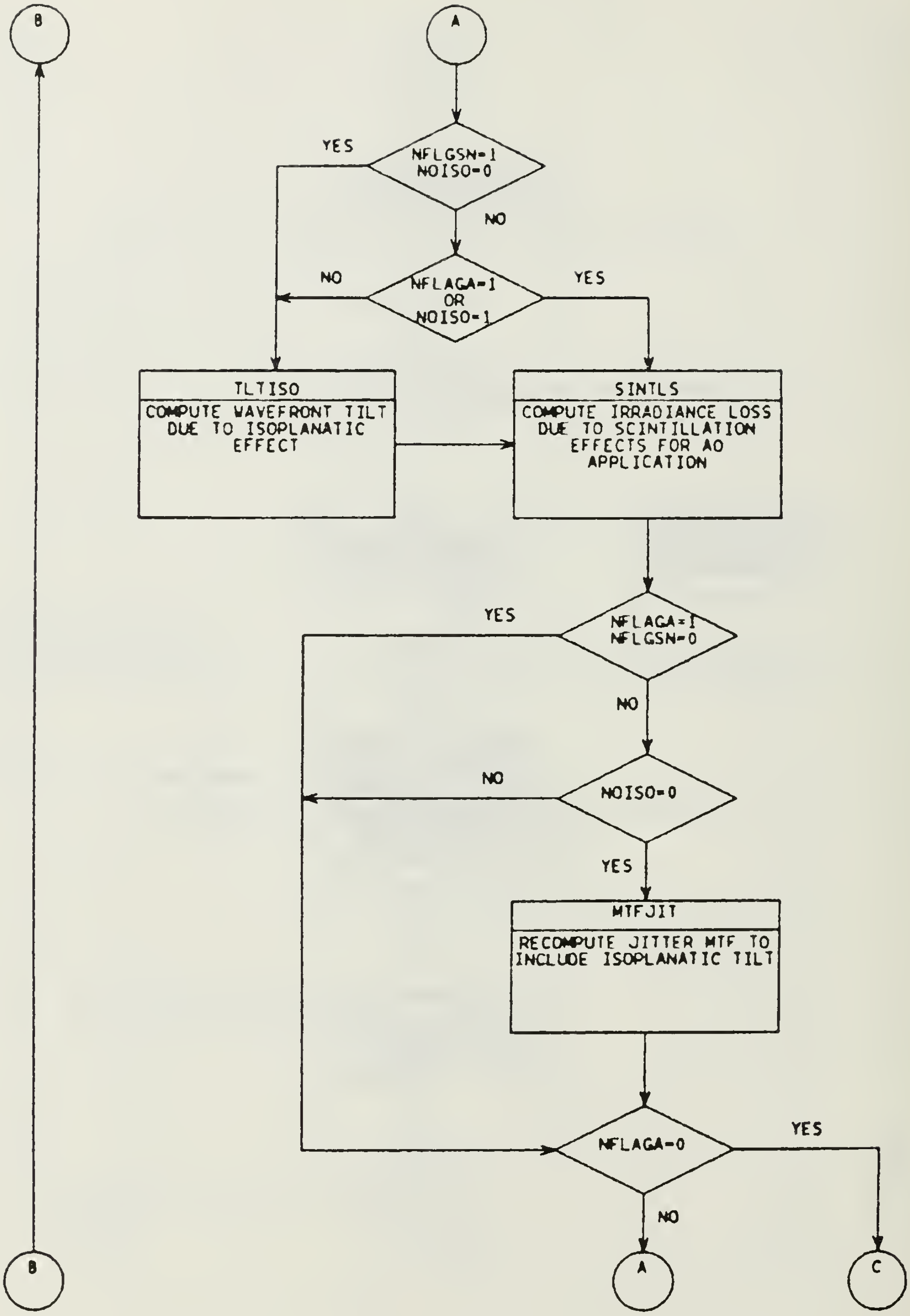


Figure 2.10 GUTSAVG Adaptive Optics Algorithm (cont).

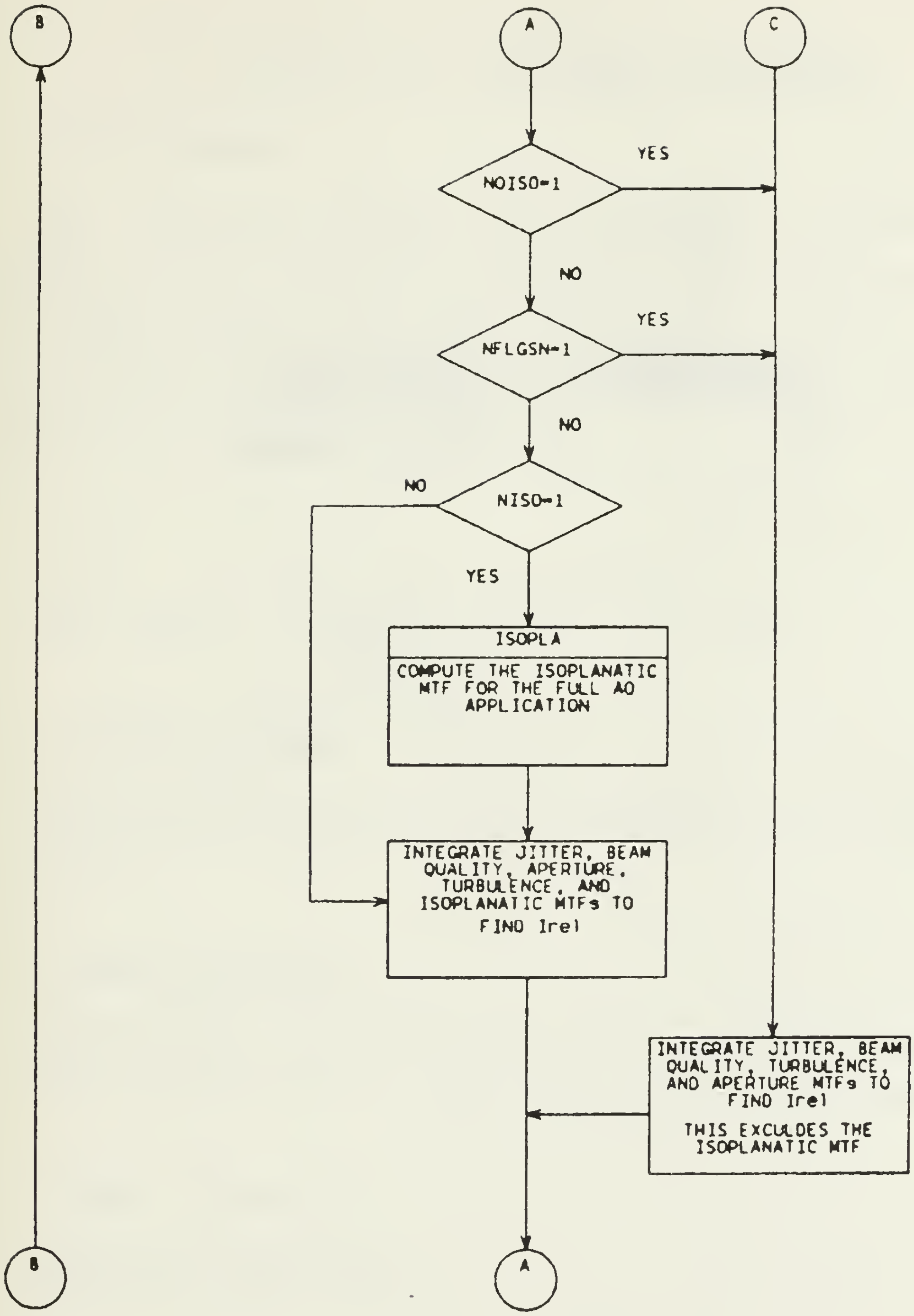


Figure 2.11 GUTSAVG Adaptive Optics Algorithm (cont).

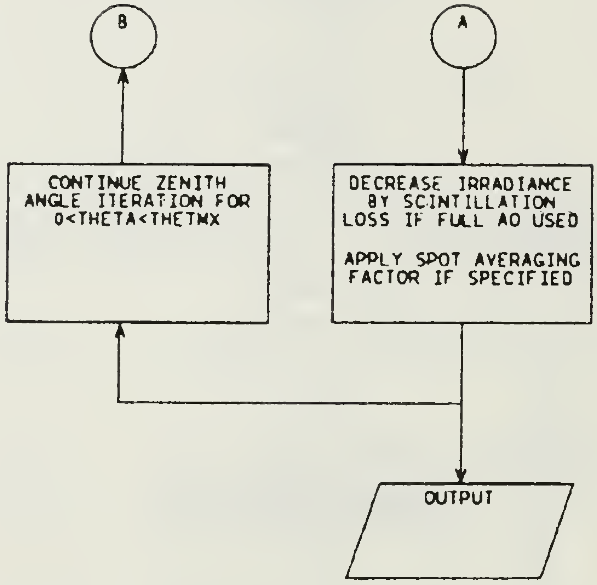


Figure 2.12 GUTSAVG Adaptive Optics Algorithm (cont).

## III. PROGRAM AND SUBPROGRAM DESCRIPTION

### A. PROGRAM INPUTS

The following are the inputs necessary to utilize GUTSAVG. Default values are indicated for parameters not absolutely required for program operation. At NPS these input parameters are entered via an input file. A copy of this file is provided in Appendix A. (*) indicates a nondimensional parameter.

• DIA (meters)

The diameter of the transmitter aperture.

• DIAOBS (meters)

The diameter of the central obscuration of the transmitter.

• BEAMSZ (meters)

The Gaussian waist diameter of the amplitude distribution at the aperture. (measured at the $1/e^2$ point)

• WAVE (meters)

The laser wavelength.

• PTOTAL (Watts)

The total power at the aperture.

• TDFLMT (*)

This is the often used "times diffraction limited number" and represents total beam quality. As used in GCTS, it is related to the RMS phase distortion at the aperture by the Strehl approximation

$$\frac{1}{(\mathrm{TDFLMT})^2} = \exp\left[-\left(\frac{2\pi\delta_{rms}}{\lambda}\right)^2\right] \qquad (3.1)$$

$(\mathrm{TDFLMT})^2$, therefore, is equivalent to the ratio of the on-axis diffraction limited intensity to the on-axis intensity resulting from the near-field phase distortion, $\delta_{rms}$.

$$\frac{1}{(\mathrm{TDFLMT})^2} = \frac{I}{I_0} \qquad (3.2)$$

For a discussion on the limitation of 3.1, see [Ref. 19].

• WAVEBQ (*)

This term is the RMS phase distortion at the laser aperture, nondimensionalized by the wavelength.

$$\mathrm{WAVEBQ} = \frac{\delta_{rms}}{\lambda} \qquad (3.3)$$

• SCALEQ (meters) default = DIA/5

This term is the transverse phase correlation length at the aperture.

• THSEE (arcsec)     default = f(RHOO)

This is a qualitative term used by astronomers to describe 'seeing conditions' in the visible range. If a point source is viewed from the earth, it may not appear as a point source but as a 'smear' or spot. The angular spread of this spot is the parameter THSEE. If RHOO is not specified as an input and THSEE is, the program will use THSEE to compute RHOO. Other than this case, THSEE is not used but will be computed as a function of RHOO and included as an output.

• HGRND (meters)

The height of the ground at the transmitter position above MSL.

• HTRANS (meters)

The height of the transmitter above.

• HSAT (meters)

The orbital altitude of the satellite above MSL (at zenith).

• THETMX (degrees)

THETMX is the angle measured from zenith below which the laser will not transmit for a zenith pass. For offset flight paths, it should be noted that the transmitter will point below this value. For an illustration of the engagement envelope, see figure 3.1

• IOFF (meters)

For a target that does not pass direct overhead, this input specifies the amount that the target ground track is offset from the ground track of the overhead case. It is the distance, as measured from the transmitter, to a perpendicular intersection on the ground track.

• RHCO (meters) default = f(THSEE) or RHOTRE

This is the turbulence coherence length as defined by H. T. Yura. [Ref. 20]. (see turbulence section for more discussion and references)

• V0 (m/sec)

The atmospheric wind. The direction of the wind is parallel and opposite to the direction of target motion. Note, in the present program, V0 is a constant independent of altitude.

• AOBLOM (*) 0.0 to 1.0

This parameter allows the user to correct for thermal blooming as if by adaptive optics. The value entered may range from 0.0 to 1.0. If 0.0 is used, complete thermal blooming compensation will occur. Conversely, if 1.0 is entered, no compensation will be applied. The variance of the phase distortion is multiplied by this correction factor before the Strehl relation is used to compute the relative intensity reduction due to thermal blooming.

$$\frac{I}{I_0} = \exp(-\sigma^2 * \text{AOBLOM}) \qquad (3.4)$$

• AVGSPT (*) 0.0 to 1.0

AVGSPT allows the user latitude in defining the far-field spot size to other than that indicated by GUTSAVG analysis. A value of 1.0 would result in the peak irradiance according to the program analysis. An entered value of .5, for example, would result in a peak irradiance 50% less than the program would otherwise indicate. AVGSPT, then, is an adjustment factor that allows the user to account for effects not addressed in the GUTSAVG propagation calculations.

• SIGJIT (radians)

SIGJIT is the $2\sigma_p$ variance for pointing and tracking jitter.

• ADAP (*) 0.0 to 1.0

This term is a correction factor for tilt due to turbulence. It represents the residual tilt after AO compensation. ADAP may be varied from 0.0 to 1.0. A value of 1.0 would result in no tilt due to turbulence being removed while a value of 0.0 would result in total tilt due to turbulence compensation. If full AO is selected the program will set ADAP equal to 0.0.

• NFLAGA (*) 0 or 1

NFLAGA is a selection indicator for full zonal adaptive optics. Enter a 0 if AO is not desired, enter a 1 if AO is desired. If AO is used, XJT,BWIDTH, and NA must be specified.

• NOISO (*) 0 or 1

NOISO is a selection indicator for isoplanatic calculations. Enter a 1 to inhibit isoplanatic calculations; enter a 0 if isoplanatic calculations are desired.

• XJT (Watts/sterad)

XJT is the target radiant intensity. It is one of the factors used to determine how noise affects the response of the AO system.

• BWIDTH (Hz)

BWIDTH is the bandwidth of the adaptive optics system.

• NA (*)

NA is the number of AO actuators used to perform phase adjustment.

• ABSIOZ (*)

This is the percent transmission at zenith at the sensing wavelength of the AO system. This term is used in the determination of relative noise at the AO sensor.

• N1 (*)

The number of iteration steps for the angle loop of the program from THETMX to 0.

• N2 (*)

The number of altitude intervals for absorption and scattering determination.

• N3 (*)

The number of altitude intervals for the turbulence calculations.

• N4 (*)

The number of iteration intervals for the MTF calculations.

• N5 (*)

The number of intervals for the slant path update of thermal blooming.

## E. ENGAGEMENT GEOMETRY

The target engagement geometry is that of a earth-based transmitter and a target satellite at a given orbit. No attempt is made to define an engagement envelope based on threshold irradiance or fluence[1]. The input parameters defining the engagement window in GUTSAVG are THETMX, ICFF, and HSAT. The general geometry of this window is shown in Figure 3.1 . Only half of the total transit window is addressed in the program calculations; the results are the

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[1] The GUTSFP (footprint) version of guts was written to do this. Except for this feature, the propagation calculations are identical to GUTSAVG.

same for either half. The program output reflects this half-window evaluation except for parameters such as total fluence and shot time which are simply double the computed values.

Figure 3.2 defines the earth center angle (ECANG). ECANG is a function of the user input THETMX. Most of the geometric calculations are referenced to earth center. Therefore, this angle is used for computing such positioning data as the angle interval at which the irradiance will be evaluated (see Figure 3.3).

Offset flight paths require a coordinate translation as shown in Figure 3.4 . Position and velocity relative to the transmitter are computed as in Figure 3.5 . It should be noted that if the flight path is offset, the zenith angle will exceed THETMX for part or all of the window. This is because the window is defined in the x-z plane only.

$H_s$ - Zenith altitude of target

$\theta_m$ - Maximum zenith angle for engagement (zenith path)

$L_o$ - Offset distance

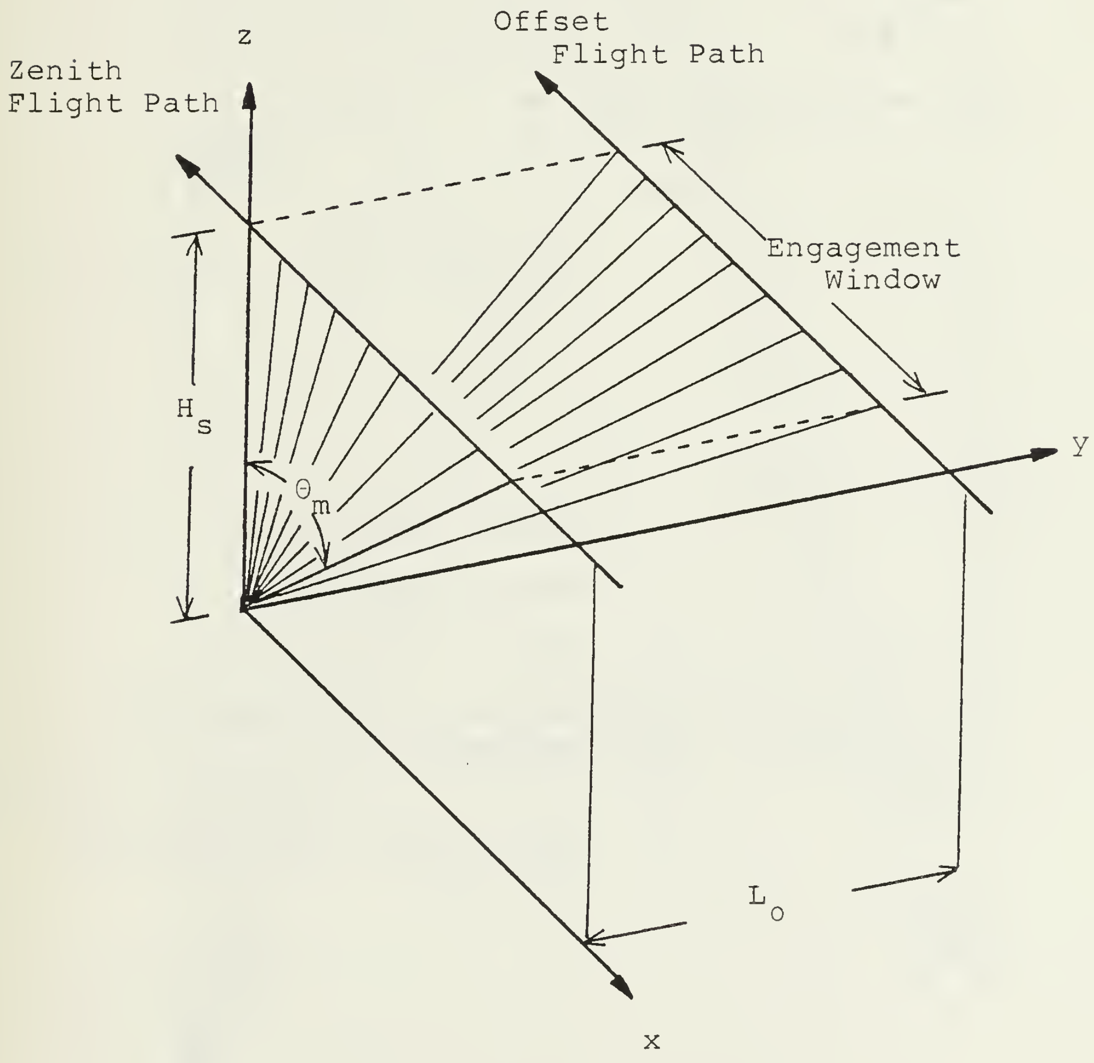
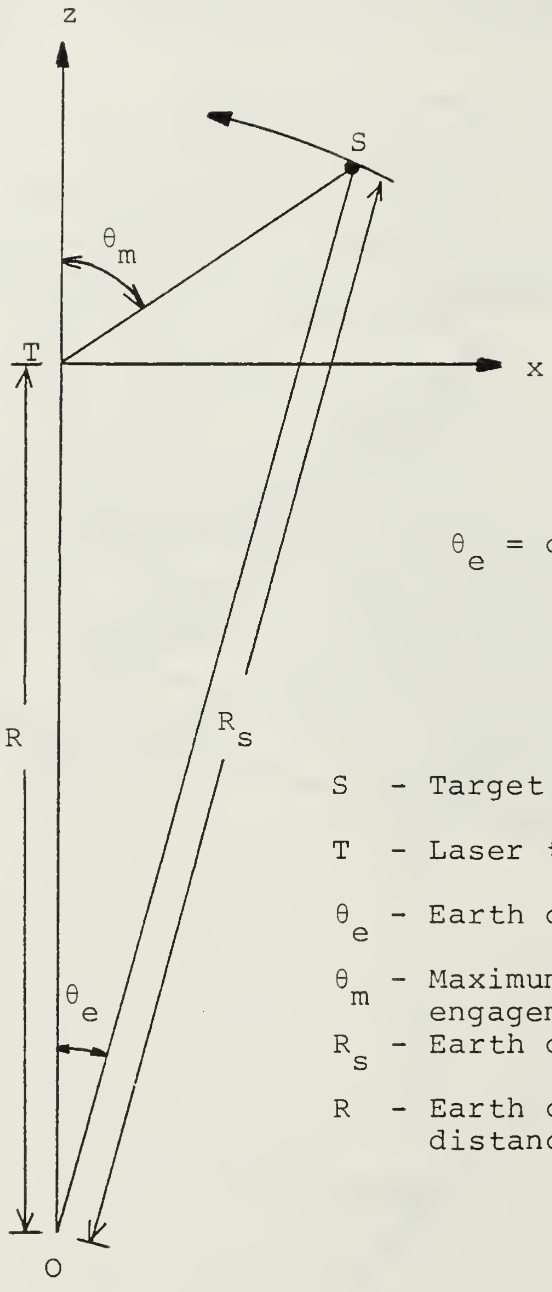



Figure 3.1 General Engagement Geometry.




$$\theta_e = \cos^{-1} \frac{R}{R_s} \sin\theta_m + \theta_m - \frac{\pi}{2}$$

S - Target satellite

T - Laser transmitter

$\theta_e$ - Earth center angle

$\theta_m$ - Maximum zenith angle for engagement

$R_s$ - Earth center-to-target distance

R - Earth center-to-transmitter distance

Figure 3.2 Earth Center Angle (ECANG).

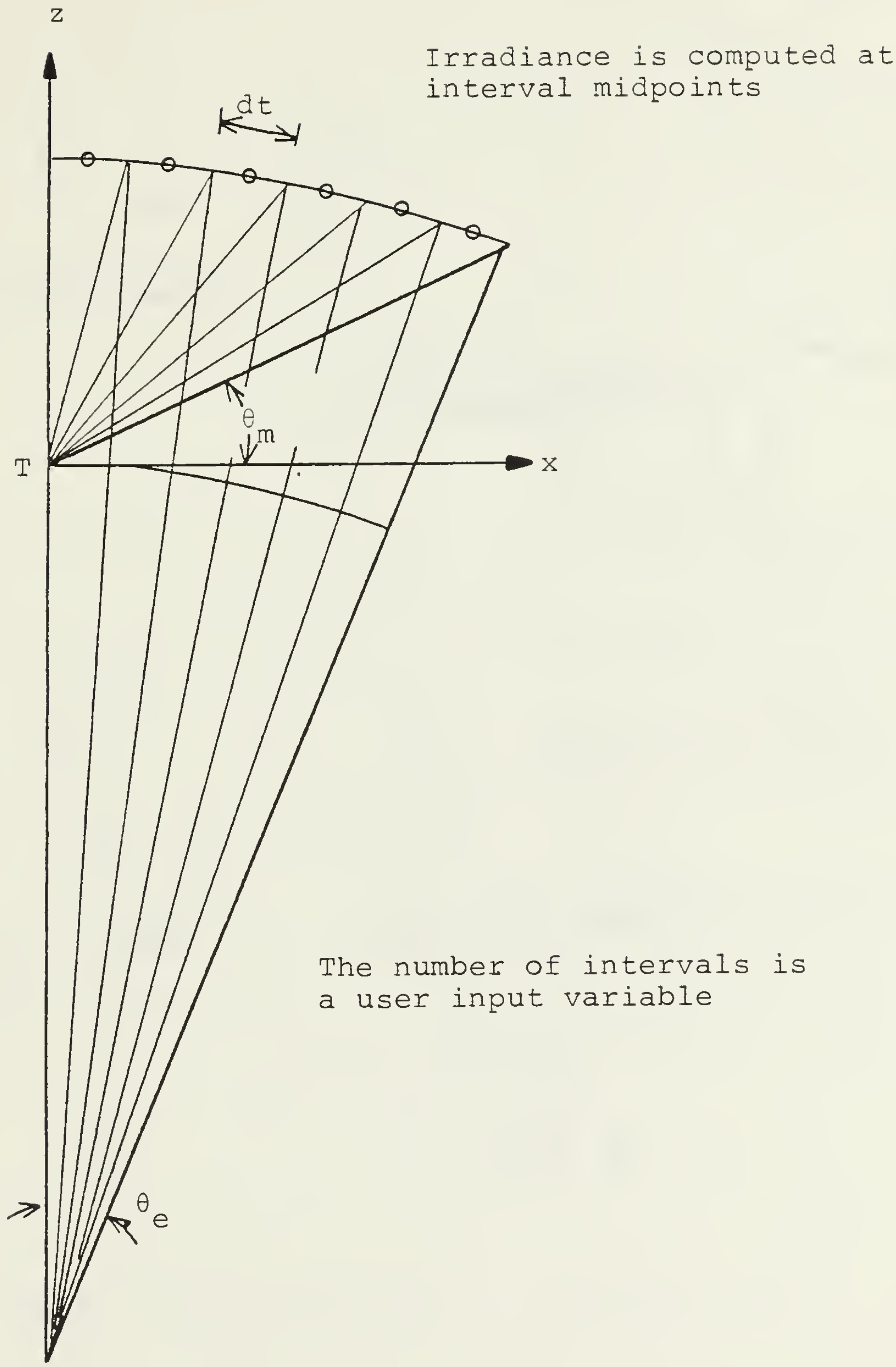
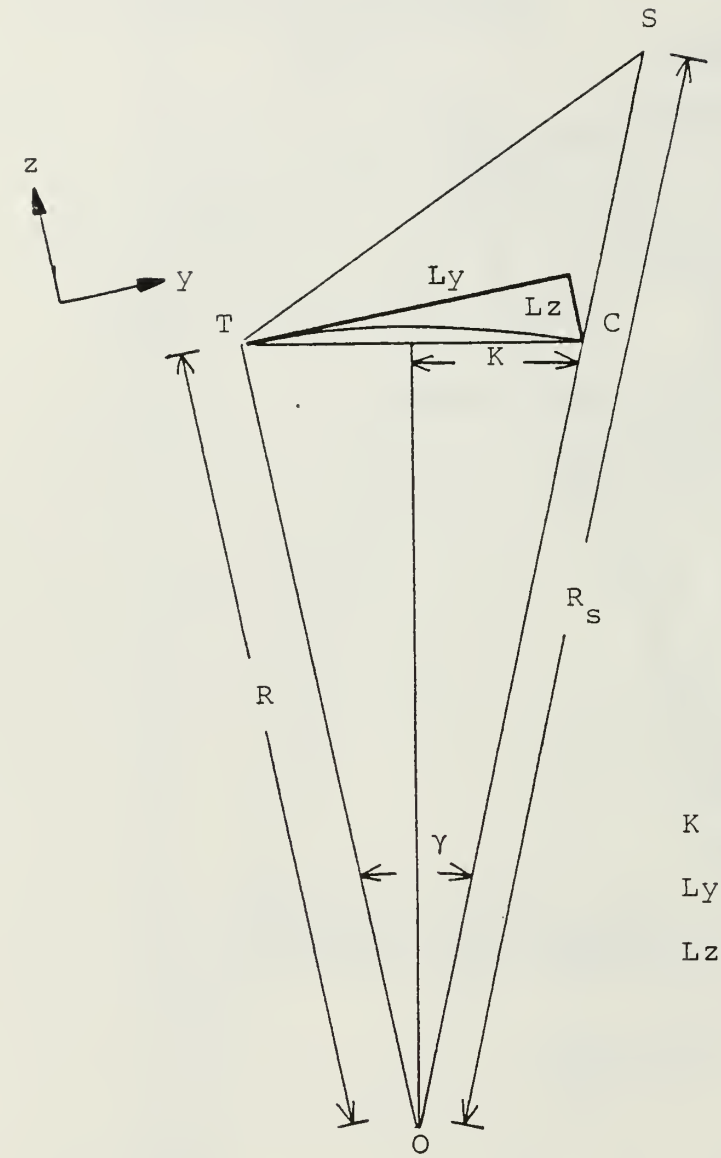



Figure 3.3 Angle Intervals for Irradiance Evaluation.



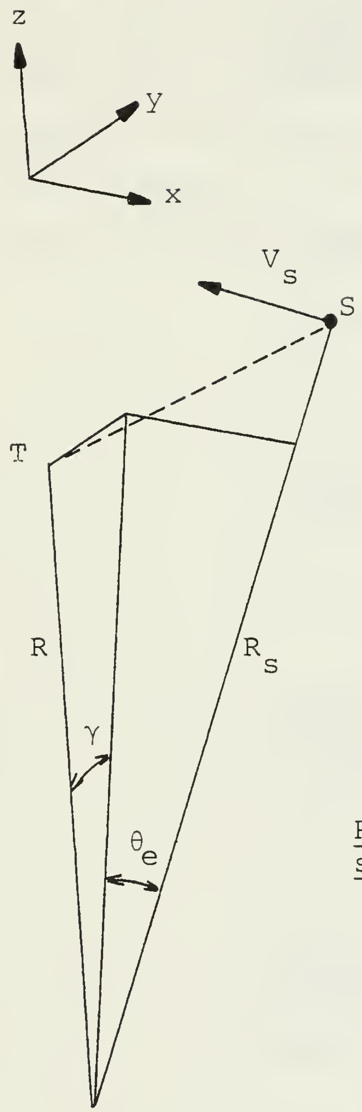

Offset is from T to C

$K = R\sin(\gamma/2)$

$Ly = \cos(\gamma/2) \cdot 2K$

$Lz = \sin(\gamma/2) \cdot 2K$

Figure 3.4 Coordinate Translation due to Flight Path Offset.




<u>Velocity components</u>

$$V_x = -V_s \cos(\theta_e)$$

$$V_y = V_s \sin(\theta_e)\cos(\gamma)$$

$$V_z = V_s \sin(\theta_e)\sin(\gamma)$$

<u>Position</u>

$$X = R_s \sin(\theta_e)$$

$$Y = Ly\cdot\cos(\gamma) + (Z_0 - R - Lz)\cdot\sin(\gamma)$$

$$Z = -Ly\cdot\sin(\gamma) + (Z_0 - R - Lz)\cdot\cos(\gamma)$$

where $Z_0 = R_s \cos(\theta_e)$

<u>Range from transmitter(T) to satellite(S)</u>

$$R_{ts} = Z + X + Y$$

(For Ly and Lz definition, see Figure 3.4)

Figure 3.5 Velocity and Position Relative to Transmitter.

## C. MAIN PROGRAM FLOW DIAGRAM

The main program mostly consists of geometry calculations and decision flow points. The decision points allow branching to adaptive optics and isoplanatic subroutines. Most of the propagation calculations are done within the subroutines. Only two major iteration loops reside in the main program, the angle interval loop and the combined MTF integration loop. The following is a general flow diagram for the main program. Decision variables are user inputs or program defined parameters.

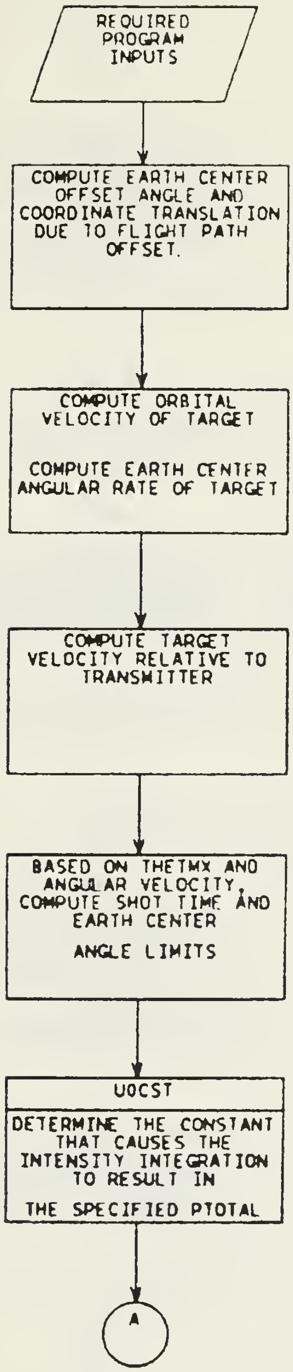



Figure 3.6 Main Program Flow Diagram.

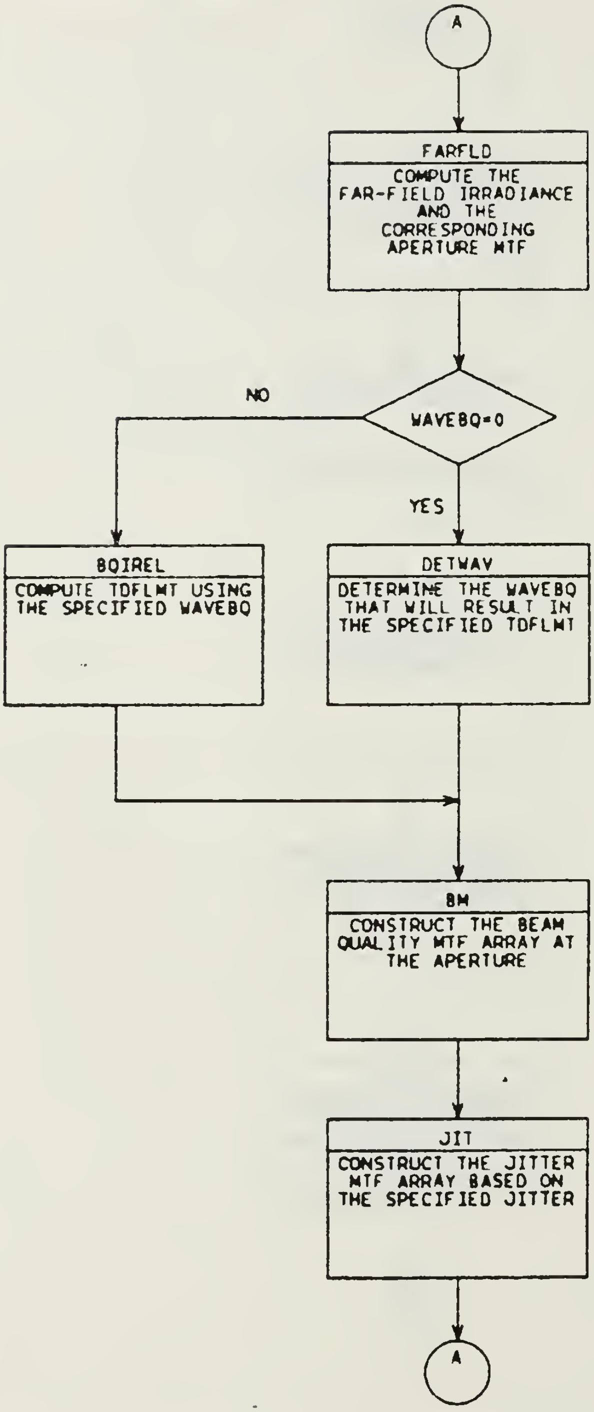



Figure 3.7 Main Program Flow Diagram (cont).

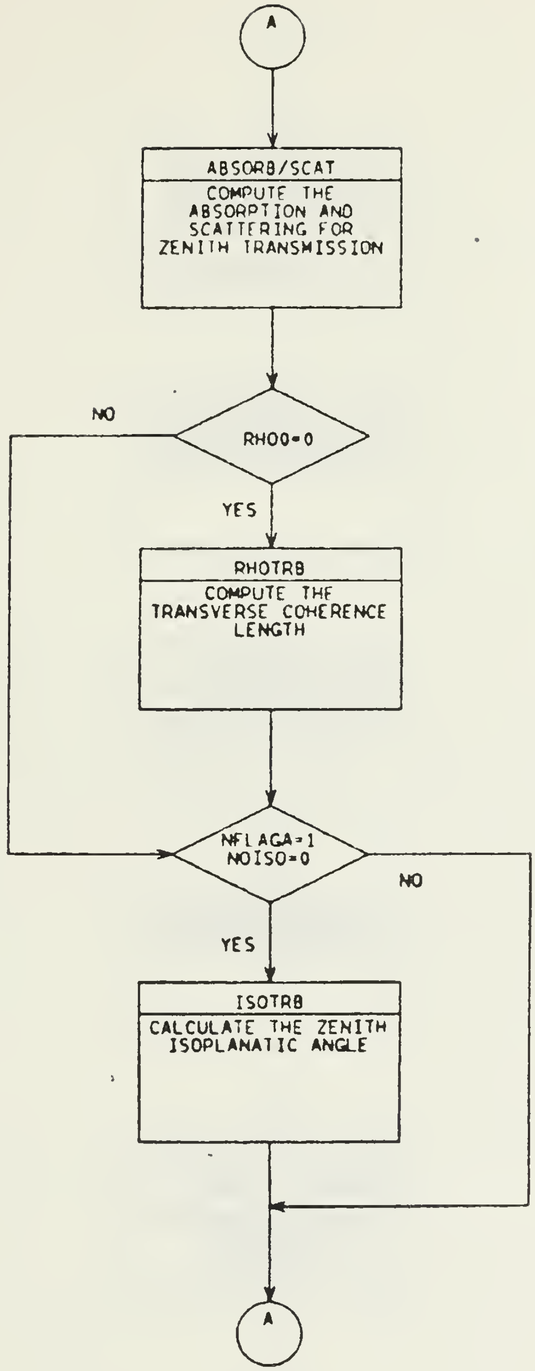



Figure 3.8 Main Program Flow Diagram (cont).

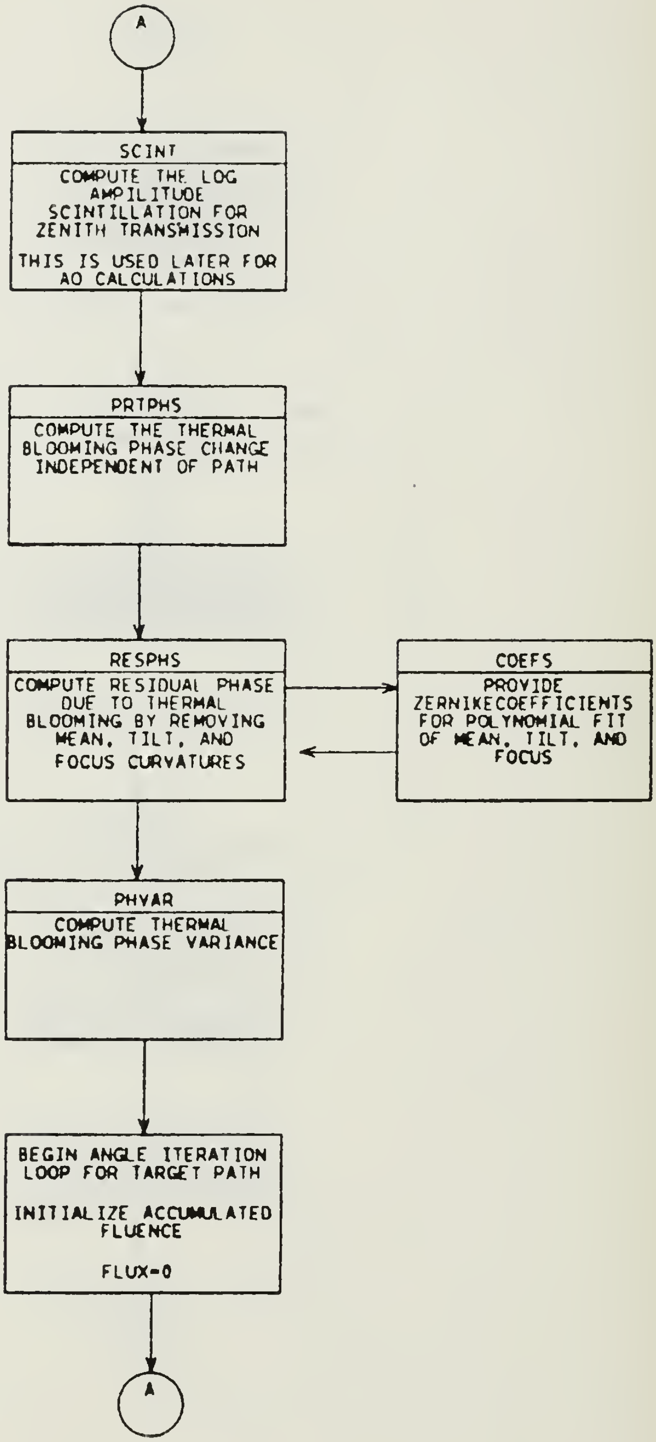



Figure 3.9 Main Program Flow Diagram (cont).

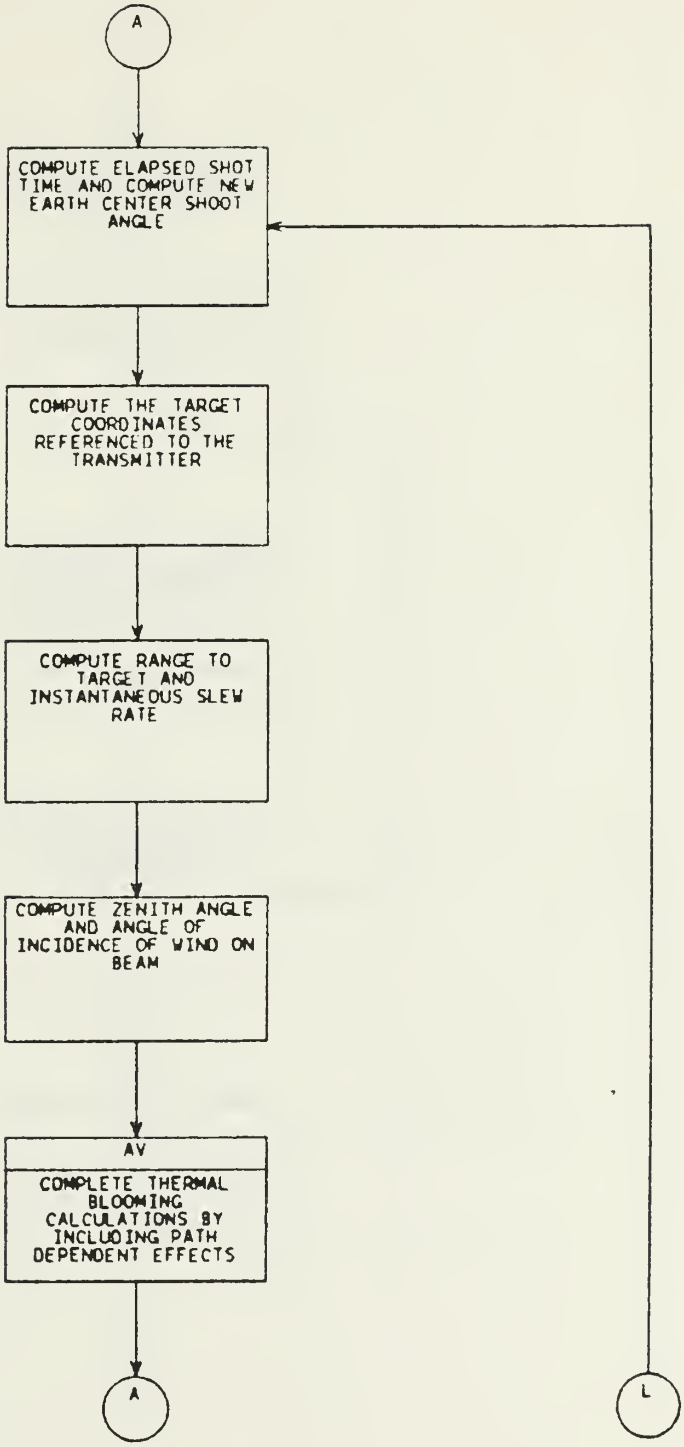



Figure 3.10 Main Program Flow Diagram (cont).

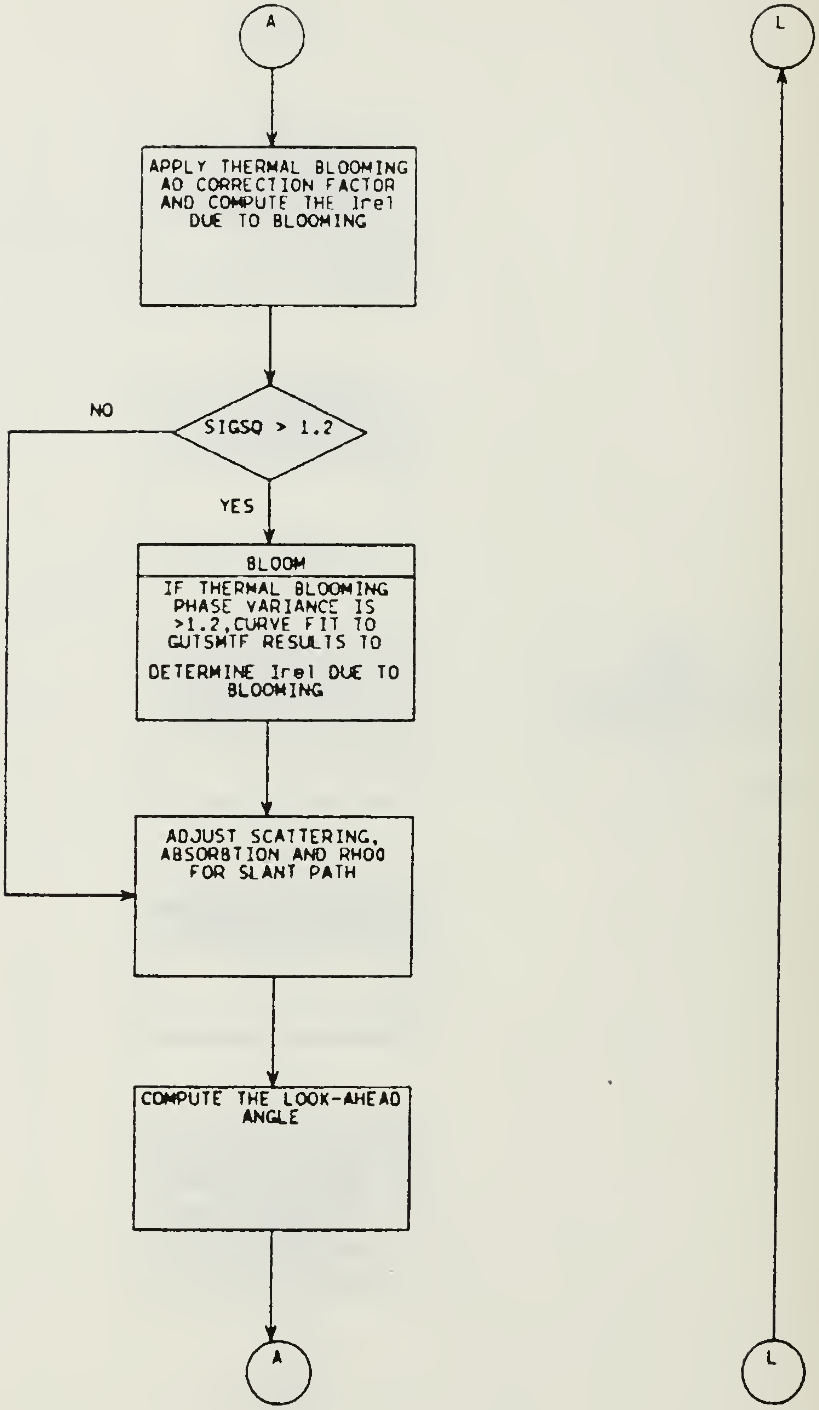



Figure 3.11 Main Program Flow Diagram (cont).

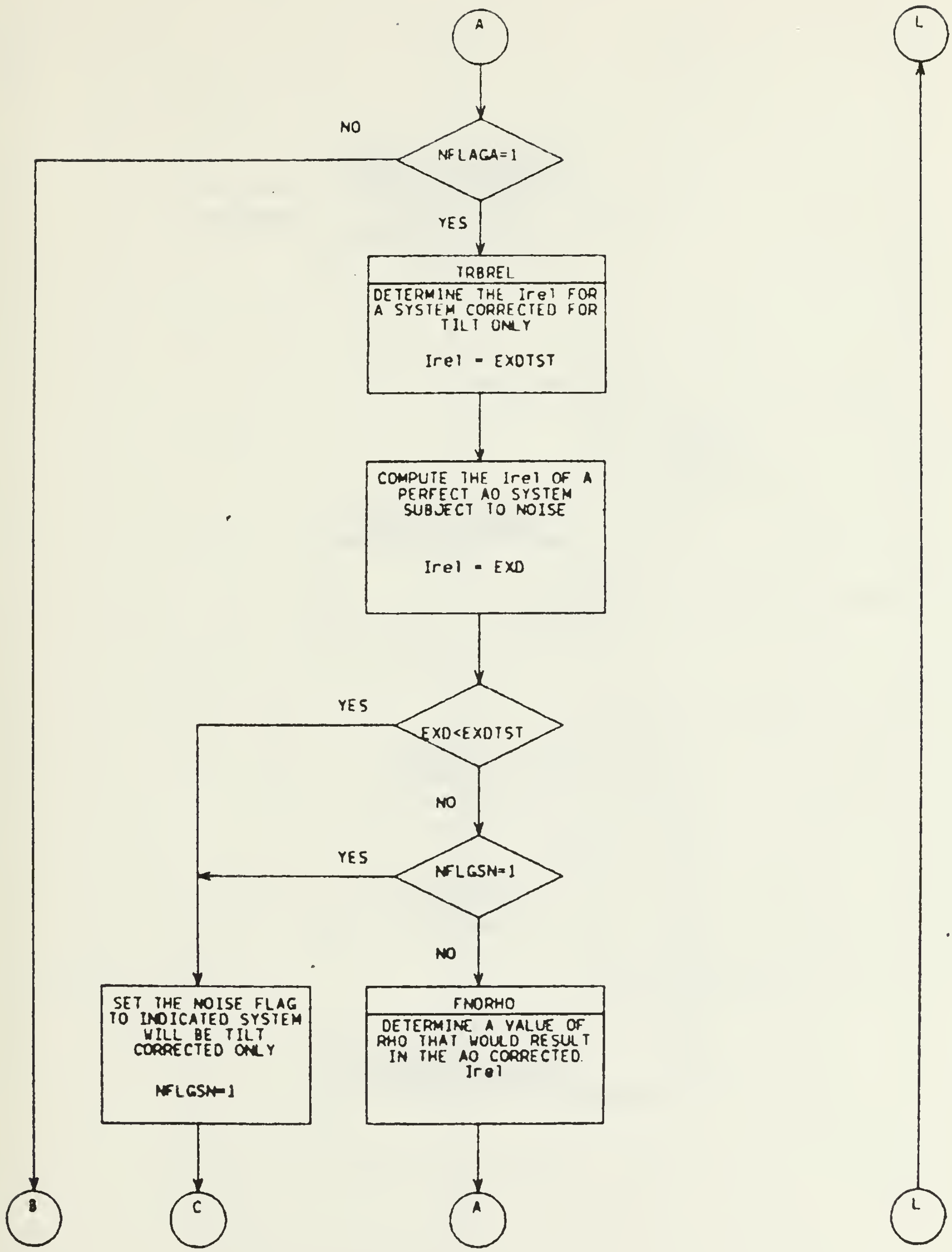



Figure 3.12 Main Program Flow Diagram (cont).

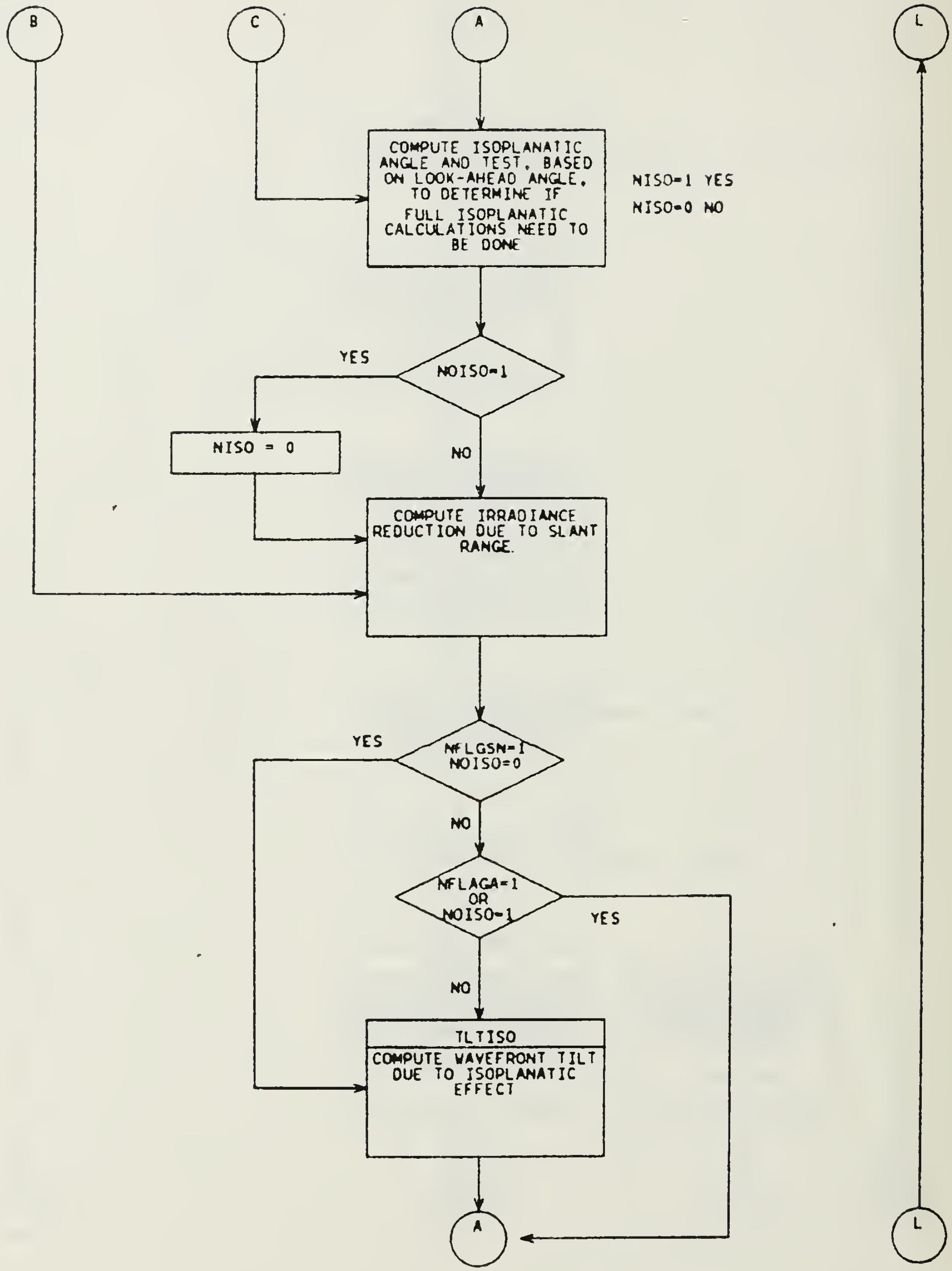



Figure 3.13 Main Program Flow Diagram (cont).

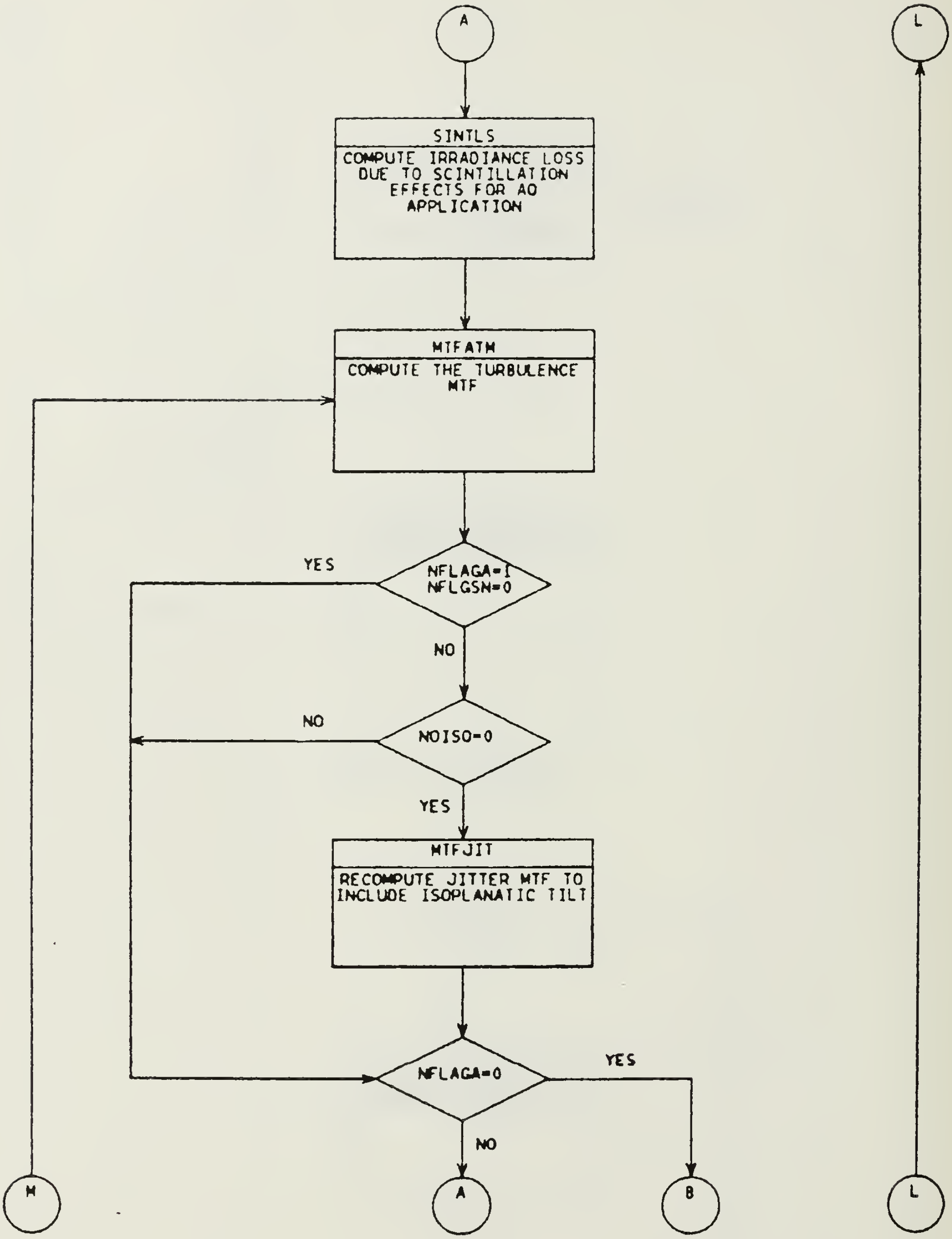



Figure 3.14 Main Program Flow Diagram (cont).

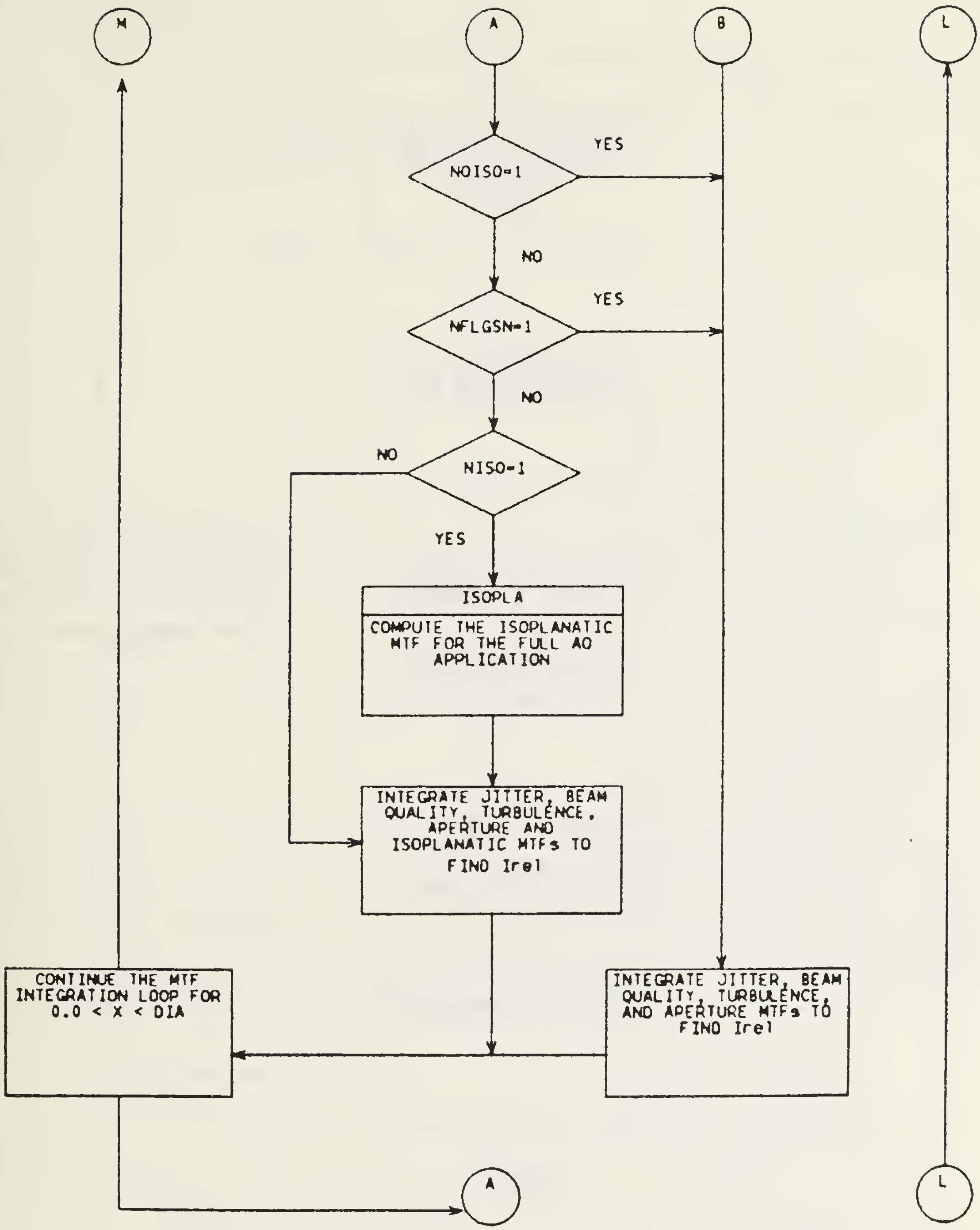



Figure 3.15 Main Program Flow Diagram (cont).

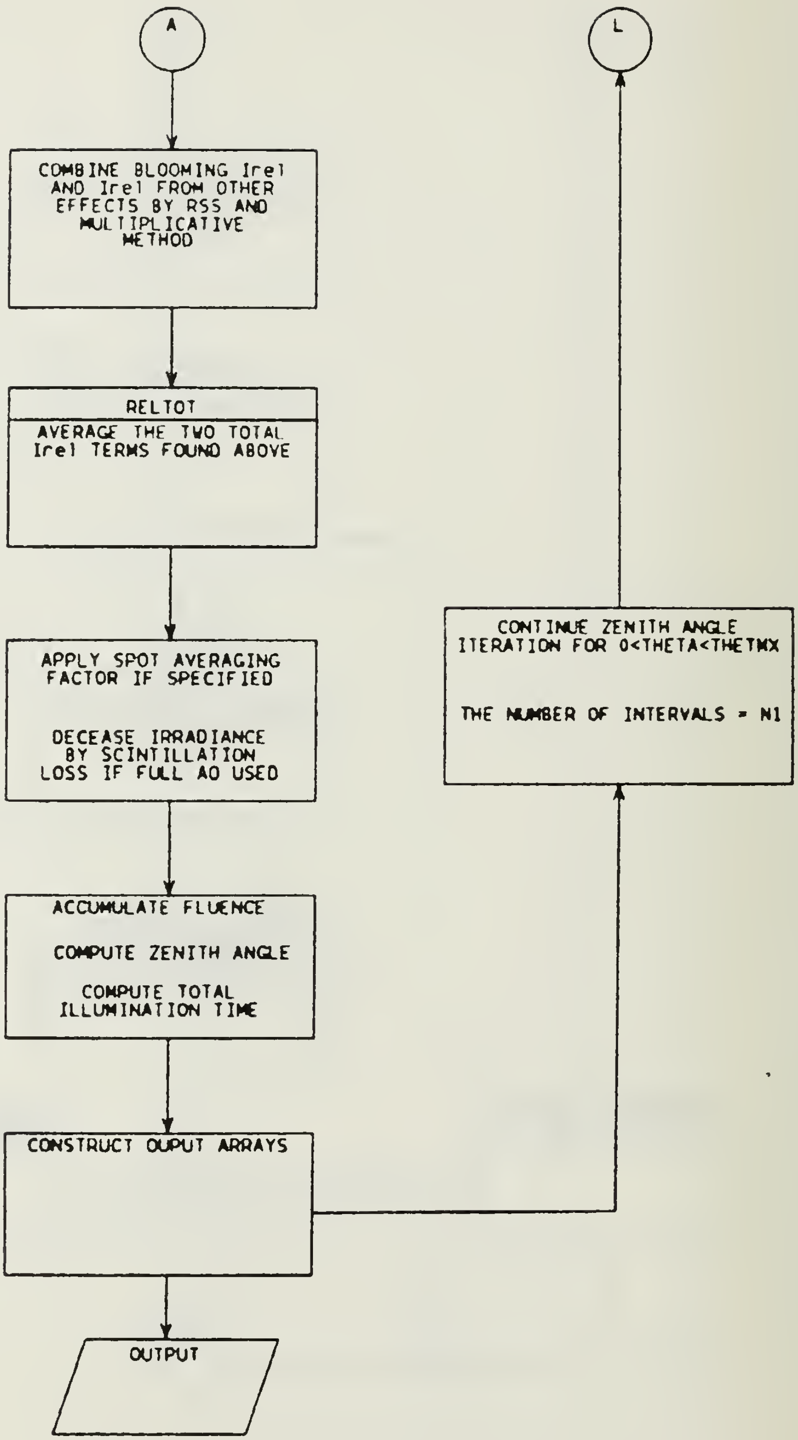



Figure 3.16 Main Program Flow Diagram (cont).

## D. SUBROUTINE DESCRIPTION

### 1. ABSORB and SCAT

As noted in the preceding chapter, absorption and scattering effects are treated indentically. The ABSORB and SCAT algorithms perform the integration

$$T_a = \exp - \int_{h_t}^{h_{atm}} \alpha(h)\,dh \qquad (3.5)$$

$$T_s = \exp - \int_{h_t}^{h_{atm}} \sigma(h)\,dh \qquad (3.6)$$

The result is the transmission due to the total absorption or total scattering. The correction for slant range is applied within the angle interval loop of the main program and is simply

$$T = T^{(\sec\theta)} \qquad (3.7)$$

is the zenith angle of the target with respect to the transmitter.

The extinction coefficients for absorption ($\alpha$) and for scattering ($\sigma$) are provided to the subroutines by a call to routines ALFA and ALFS respectively.

## TABLE I

### ABSORB and SCAT Program Variable Definitions

| Variable | Fortran name Sub | Fortran name Main | Definition |
|---|---|---|---|
| $T_a$ (ABSORB) | T | TABSC | Total molecular transmission |
| $T_s$ (SCAT) | T | TSCATO | Total scattered transmission |
| $h_{atm}$ (meters) | HATMO | HATMO | Height of atmosphere |
| $h_t$ (meters) | HT | HTRANS | Height above MSL of transmitter |
| $\alpha(h)$ $(km)^{-1}$ | ALP | - | Absorption coef. at given altitude |
| $\sigma(h)$ $(km)^{-1}$ | ALS | - | Scattering coef at given altitude |
| - | N | N2 | # of integration intervals |

2. ALFS and ALFA

These two routines are also identical. They provide the extinction coefficients to ABSORB and SCAT for a specified altitude. At each altitude where a coefficient value is desired, a linear interpolation is performed between data points supplied by the user. Data statements precede each of these subprograms, and it is with these statements that the absorption and scattering data should be entered. Units for the coefficient and corresponding altitude should be $km^{-1}$ and km respectively.

TABLE II

ALFS and AIFA Program Variables and Definitions

| Variable | Fortran name Sub | Fortran name Main | Definition |
|---|---|---|---|
| $\sigma(h)$ $(km)^{-1}$ | S | AIS | Scattering coef. at specified altitude |
| $\alpha(h)$ $(km)^{-1}$ | A | AIP | Absorption coef. at specified altitude |
| h (meters) | H | - | specific altitude |
| — | ALT(NL) | - | Altitude data list |
| — | ATA(NL) | - | Absorption data list |
| — | ATS(NL) | - | Scattering data list |
| — | NL | - | Number of points in data list |

3. UOCST

For a gaussian beam with constant phase, the initial amplitude distribution at the transmitter aperture is

$$U(r) = U_0 \exp\left[-(r/w)^2\right] \tag{3.8}$$

where $U_0$ is the amplitude and w is the spot size [Ref. 21]. The purpose of UOCST is to compute the constant $U_0$ for a given aperture power.

By the scalar wave approximation, the intensity distribution is [Ref. 22]

$$I(r) = |U(r)|^2 \qquad (3.9)$$

To relate the field distribution to the power, the intensity distribution is integrated over the aperture.

$$P_t = \pi \int_{r_i}^{r_o} I(r)\, dr^2 \qquad (3.10)$$

Substituting 3.8 and 3.9 into 3.10

$$P_t = \pi \int_{r_i}^{r_o} U_0 \exp\left[-(r/w)^2\right] \quad dr^2 \qquad (3.11)$$

then rearranging terms, produces the expression for $U_0$.

$$U = \left[P_t \left\{\pi \int_{r_i}^{r_o} \left(\exp\left[-(r/w)^2\right]\right)^2 dr^2\right\}^{-1}\right]^{\frac{1}{2}} \qquad (3.12)$$

The integration limits $r_o$ and $r_i$ are the radius of the transmitter and the obscuration, respectively.

UOCST performs the integration in 3.12 using the trapezoidal rule. A call is made to subroutine FIELD to evaluate $\exp[-(r/w)^2]$ which is simply $U(r)$ with $U_0 = 1$. For this reason, $U_0$ is defined as unity when FIELD is called by UOCST.

TABLE III

UOCST Program Variables and Definitions

| Variable | Fortran name Sub | Fortran name Main | Definition |
|---|---|---|---|
| $U_0$ $(W)^{\frac{1}{2}}m^{-1}$ | U0 | - | Normalization constant |
| $P_t$ (Watts) | P | PTOTAL | Total aperture exit power |
| - | N | NI | # of integration increments |
| $r_o$ (meters) | RO | - | Outer radius of transmitter |
| $r_i$ (meters) | RI | - | Radius of obscuration |
| $U(r)$ $(W)^{\frac{1}{2}}m^{-1}$ | UR | - | Field amplitude at radius r |
| w (meters) | BMRAD | - | Radius of spot at aperture |

4. FIELD

FIELD calculates the field distribution for a axi-symmetric Gaussian beam with constant phase.

$$U(r) = U_0 \exp\left[-(r/w)^2\right] \qquad (3.13)$$

**TABLE IV**

**FIELD Program Variable Definitions**

| Variable | Fortran name Sub | Fortran name Main | Definition |
|---|---|---|---|
| $U(r)$ $(W)^{\frac{1}{2}} m^{-1}$ | UR | - | Field amplitude at r |
| $U_0$ $(W)^{\frac{1}{2}} m^{-1}$ | U0 | - | Normalization constant |
| w (meters) | BMRAD | - | Radius of spot at aperture |

5. FARFLD

In the Fraunhofer region, the amplitude distribution can be found by taking the Fourier transform of the aperture distribution [Ref. 23]. Using polar coordinates and noting axial symmetry, $U(\rho)$ in the far-field can be expressed as

$$U(\rho) = \frac{1}{\lambda z} \int_a^b \int_0^{2\pi} U(r) \exp\left[-\left(\frac{i2\pi}{\lambda z}\right) \cdot r\rho \cdot \cos\theta\right] r dr d\theta \qquad (3.14)$$

Using integral relation for the zero order Bessel function, equation 3.14 can be simplified to [Ref. 24]

$$U(\rho) = \frac{2\pi}{\lambda z} \int_a^b U(r)\, J_0\left(\frac{2\pi\rho r}{\lambda z}\right) r dr \qquad (3.15)$$

The intensity in the far-field is then given by $I(r)=|U(r)|^2$ or in terms of equation 3.15

$$I(\rho) = \left(\frac{2\pi}{\lambda z}\right)^2 \left[\int_a^b U(r) J_0\left(\frac{2\pi\rho r}{\lambda z}\right) rdr\right]^2 \qquad (3.16)$$

where b and a are the radius of the transmitter and the radius of the obscuration, respectively. [Ref. 25]

FARFLD evaluates 3.16 at a specified number of increments in the far-field and assigns these values to an array F(i). F(i) is normalized with the total aperture power so that the MTF produced would be unity at the origin. Note, however, that when the MTF is computed in this case, the MTF is normalized so as to produce an Irel (intensity relative) value when integrated.

$$M_a(\overline{\rho}) = \left(\frac{2\pi}{\lambda z}\right)^2 \frac{P_t}{I_0} \int_0^r I(\overline{\rho}) J_0\left(\frac{2\pi\overline{\rho}r}{\lambda z}\right) \overline{\rho} d\overline{\rho} \qquad (3.17)$$

$I_0$ is determined by evaluating equation 3.16 with r=0.0.

TABLE V

FARFLD Program Variables and Definitions

| Variable | Fortran name Sub | Fortran name Main | Definition |
|---|---|---|---|
| $k\,(m)^{-1}$ | CKR | - | $(2\pi/\lambda)$ |
| $\rho$ | R1 | - | Radius in far-field |
| $r$ | R0 | - | Radius in aperture |
| $I_0$ (Watts) | PMAXC | PMAXC | Far-field on-axis intensity for a diffraction limited beam |
| $I(r)$ $(W/m^2)$ | F(I) | TISC | Irradiance in far-field |
| $M_a(\overline{\rho})$ | G(I) | IRRMTF | Aperture MTF |
| - | DX2 | DX | Aperture MTF increments |
| $P_t$(Watts) | P | PTOTAL | Total power in the aperture |

6. <u>ECIREL</u>

If the 'times diffraction limited number' (TDFLMT) is not specified, this routine computes the Irel value due to beam quality which is then used to compute TDFLMT in the main program. The calculation performed is

$$\text{Irel} = 2\pi \int M_a(\overline{\rho})\; M_b(\overline{\rho})\; \overline{\rho}d\overline{\rho} \qquad (3.18)$$

where $M_a$ is the aperture MTF and $M_b$ is the MTF for the beam quality phase screen. $M_a$ is defined in subroutine FARFID so that this integration produces an Irel value. $M_b$ is the beam

quality MTF as computed by subroutine MTFBQ. IDFLMT is computed in the main program and is 1/ Irel .

TABLE VI

BQIREL Program Variables and Definitions

| Variable | Fortran name Sub | Main | Definition |
|---|---|---|---|
| N | - | IDFLMT | Times diff. limited # |
| Irel | REL | TBQ | - |
| $M_a(\overline{\rho})$ | A(I) | IRRMTF | Aperture MTF |
| $M_b(\overline{\rho})$ | F(I) | - | MTF for phase screen |
| - | N4 | N4 | # of iterations for MTF calculations |

7. DETWAV

If the RMS phase distortion parameter (WAVEBQ) is not specified, this routine computes it based on the approximation

$$Irel = \exp(-\sigma^2) \tag{3.19}$$

where $\sigma = \frac{2\pi\delta_{rms}}{\lambda}$ and $\delta_{rms}$ is the RMS value of the phase distortion at the aperture. Irel is the intensity degradation due to beam quality and is equal to $1/(N)^2$. N is the input parameter IDFLMT. DETWAV first evaluates $\sigma^2$ using equation 3.19 and then uses this value as a starting point

to compute a more accurate $\sigma^2$ by iteration using subroutine EQIREL. $\sigma^2$ is used to compute the beam quality MTF and the beam quality Irel as in equation 3.18 . $\sigma^2$ is adjusted, and the process repeated until the Irel found by equation 3.18 is equal to that determined by $1/(N)^2$.

TABLE VII

DETWAV Program Variables and Definitioms

| Variable | Fortran Name Sub | Main | Definition |
|---|---|---|---|
| $\left[\frac{2\pi\delta_{rms}}{\lambda}\right]^2$ | VAREQ | VAREQ | Constant |
| $\frac{\delta_{rms}}{\lambda}$ | WAVEEQ | WAVEEQ | Phase distortion parameter |
| $1/N^2$ | RELO | - | $1/(\mathrm{IDFLMT})^2$ |

8. MTFEQ and BM

These two routines calculate the beam quality MTF array. The MTF is [Ref. 26]

$$M_b(\overline{\rho}) = \exp\left(-k^2\left[\sigma^2 - C_\phi(\overline{\rho})\right]\right) \qquad (3.20)$$

where $C_\phi(\rho)$ is the autocorrelation function of the phase and is the phase variance. $C_\phi(\rho)$ is assumed to be Gaussian. Letting $C_\phi(\rho) = \sigma^2\exp\left[-(\rho/L)^2\right]$, where L is the phase correlation length, results in [Ref. 27]

$$M_b(\bar{\rho}) = \exp\left[-\left(\frac{2\pi\delta_{rms}}{\lambda}\right)^2 \left(1-\exp\left[-(\bar{\rho}/L)^2\right]\right)\right] \qquad (3.21)$$

$\frac{\delta_{rms}}{\lambda}$ is the wavelength RMS phase distortion and is an input parameter (WAVEEQ). L, also a user input (SCALEQ), will default to 1/5 the diameter of the aperture if not otherwise specified.

TABLE VIII

MTFEQ and BM Program Variables and Definitions

| Variable | Fortran name Sub | Main | Definition |
|---|---|---|---|
| $\left[\frac{2\pi\delta_{rms}}{\lambda}\right]^2$ | VAREQ | VAREQ | Beam quality variance |
| $M_b(\bar{\rho})$ | F(I) | BQMTF | Beam quality MTF |
| - | N4 | N4 | # of MTF integration increments |
| $k\ (m)^{-1}$ | - | - | $(2\pi/\lambda)$ |

9. ISOTRB

ISOTRB calculates the zenith isoplanatic angle for use in the adaptive optics portion of the program. The angle is given by [Ref. 28]

$$\Theta_0 = .314 \left[ \frac{2.91}{6.88} \sec\theta \int_{h_t}^{h_{atm}} C_n^2(h)\ h^{5/3} dh \right]^{-3/5} \tag{3.22}$$

For the near zenith case, $\sec\theta = 1$. $C_n^2$ is the refractive index structure constant and is calculated by subroutine CN2H as function of altitude. See Fried [Ref. 29] for a discussion of the above angle.

TABLE IX

ISOTRB Program Variables and Definitions

| Variables | Fortran Name Sub | Fortran Name Main | Definition |
| --- | --- | --- | --- |
| $\Theta_0$ (rad) | ISOANG | ISOANO | Zenith isoplanatic angle |
| $C_n^2$ (m)$^{-2/3}$ | CN2 | - | Refractive index structure constant |
| - | N | N3 | Integration intervals for turbulence |
| $\theta$ (deg) | - | OMEGA | Zenith angle |

10. SCINT and SINILS

If full adaptive optics are used, amplitude scintillation effects will act to degrade the performance of the

conventional phase correcting adaptive optics system. This subroutine computes the log amplitude variance of the scintillations for zenith transmission. The approximation used is

$$\sigma_z^2 = .56k^{7/6}\int_{h_t}^{h_{atm}} h^{5/6} C_n^2(h)\,dh \tag{3.23}$$

For the off zenith case

$$\sigma_z^2 = \sigma_z^2 \sec(\theta) \tag{3.24}$$

where $\theta$ is the zenith angle [Ref. 30]. The relative irradiance loss due to scintillation is

$$\text{AMP LOSS} = \exp\left(-\sigma_z^2 \sec(\theta)\right) \tag{3.25}$$

The correction for the off zenith case is applied in subroutine SINTLS in the angle loop of the main program when full adaptive optics are specified. This loss factor has been shown to be limited to approximately .55, therefore, a default value is used in the main program in the case where equation 3.25 yields a value less than 0.5 [Ref. 31].

TABLE X

SCINTLS and SCINT Program Variables and Definitions

| Variable | Fortran Name Sub | Fortran Name Main | Definition |
|---|---|---|---|
| $k\ (m)^{-1}$ | CK | - | $2\pi/\lambda$ |
| $C_n^2\ (m)^{-2/3}$ | CN2H | - | Refractive index structure constant |
| $\sigma_x^2$ | SIGX2 | SIGX2 | Log amplitude variation |
| Amp loss | TAMP | TAMP | Loss caused by scintillation |

11. CN2H

CN2H computes the index of refraction structure constant as a function of altitude. $C_n^2$ is determined using Hufnagel's model with an added term to include the near surface effects. [Ref. 32] [Ref. 33]

$$C_n^2 = (5.94\text{x}10^{-53})h^{10}\exp\left(\frac{-h}{1000}\right) + (2.7\text{x}10^{-16})\exp\left(\frac{-h}{1500}\right) + (10^{-14})\exp\left(\frac{-h}{100}\right) \tag{3.26}$$

Here, the units of h are meters.

12. RHOTRB

This subroutine computes Yura's [Ref. 34] lateral coherence length, $\rho_0$ , in terms of Fried's [Ref. 35] coherence diameter, $r_0$.

$$\rho_0 = r_0/2.1 \tag{3.27}$$

Substituting Fried's definition for $r_0$

$$\rho_0 = \frac{1}{2.1}\left[\frac{2.91}{6.88}\,k^2\int_{h_t}^{h_{atm}} C_n(h)\,dh\right]^{-3/5} \tag{3.28}$$

TABLE XI

RHOTRB Program Variables and Definitions

| Variable | Fortran Name Sub | Fortran Name Main | Definition |
|---|---|---|---|
| $k\ (m)^{-1}$ | CK | - | $2\pi/\lambda$ |
| $C_n^2\ (m)^{-2/3}$ | CN2 | - | Refractive index structure constant |
| $\rho_0$ (meters) | RHC | RHO | Coherence length |
| - | N | N3 | # of integration intervals for turbulence |

13. JIT and MTFJIT

JIT AND MTFJIT function algorithmically the same as EM and MTFEQ. Together, they compute the jitter MTF array. MTFJIT is called by JIT for each radial increment. The jitter MTF is given by

$$M_j(\bar{\rho}) = \exp\left(\frac{k^2\bar{\rho}^2(2\sigma_p)^2}{8}\right) \tag{3.29}$$

where $2\sigma_p$ is a user specified input. As with beam quality, this quantity is applied at the aperture.

TABLE XII
JIT and MTFJIT Program Variables and Definitions

| Variable | Fortran Name Sub | Fortran Name Main | Definition |
|---|---|---|---|
| $k$ $(m)^{-1}$ | CK | - | $2\pi/\lambda$ |
| $M_j(\overline{\rho})$ | F | JITMTF | Jitter MTF |

14. PHIEHS

This subroutine calculates that part of thermal blooming not dependent on the slant path of the beam. The equation used by GUTSAVG for the phase distortion due to thermal blooming is

$$\Delta\phi(x,y) = \left[\frac{2\pi}{\lambda}\,\frac{n-1}{p_0}\,\frac{\gamma-1}{\gamma}\int_{-\infty}^{x'} I(x',y)\,dx'\right] \times \left[\int_{h_t}^{h_{atm}} \frac{\alpha(h)\exp\left(-\sec\theta\int_{h_t}^{h} \alpha(h)+\sigma(h)\ dh\right)}{V_0\cos\xi + \omega h}\,dh\right] \qquad (3.30)$$

Note that the first term in this expression is invariant with respect to beam path while the second term contains such path dependent variables as wind , wind due to slew, and extinction coefficients. The first term is evaluated by this subroutine and the remainder evaluated later in the program inside the shoot angle iteration loop by subroutine AV.

Standard values used for $n_0-1$, $p_0$, and $\gamma$ are $2.72\times10^{4}$, $1.01\times10^{5}$ J/m³, and 1.4, respectively. A phase screen, P(i,j), is constructed by iteration of the intensity integral. Note that program performs this integration over a half plane of the aperture defined by -b<y<b and 0<x<b where b is the aperture diameter. The results are adjusted later in subroutine PHVAR for this method.

TABLE XIII

PRTPHS Program Variables and Definitions

| Variable | Fortran Name Sub | Main | Definition |
| --- | --- | --- | --- |
| $k\ (m)^{-1}$ | CK | - | $2\pi/\lambda$ |
| $n_0-1$ | const. | - | Refractive index term ($2.72\times10^{4}$) |
| $\gamma$ | const. | - | Ratio of specific heats (1.4) |
| $p_0$ | const. | - | Atmos. pressure ($1.01\times10^{5}$) N/m² |
| $\phi\ (x,y)$ | PH(i,j) | PH(i,j) | Thermal blooming phase array |

15. RESPHS and COEFFS

Once the phase screen has been constructed by subroutine PRTPHS, subroutine RESPHS removes the mean, tilt, and focus curvature. The result is the phase aberration due to thermal blooming alone. Zernike polynomials are utilized for expressing these phase distortions with subroutine COEFFS providing the required coefficients. These polynomials are

$$Z_0(x,y) = a_0 \qquad \text{(mean)} \qquad (3.31)$$

$$Z_1(x,y) = a_1 x \qquad \text{(x tilt)} \qquad (3.32)$$

$$Z_2(x,y) = a_2 y \qquad \text{(y tilt)} \qquad (3.33)$$

$$Z_3(x,y) = a_3 (x^2+y^2)+a_4 \qquad \text{(focus)} \qquad (3.34)$$

The expansion coefficients are given below and are computed relative to a uniform aperture weighting function $W(x,y)$. $W(x,y) = 1$ inside the aperture and zero elsewhere. The integrals have been multiplied by 2 to compensate for the half plane integration of subroutine PHRPHS.

$$f_0 = 2a_0 \quad \phi(x,y)W(x,y)\,dxdy \qquad (3.35)$$

$$f_1 = 2a_1 \quad \phi(x,y)W(x,y)\,xdxdy \qquad (3.36)$$

$$f_2 = 2a_2 \quad \phi(x,y)W(x,y)\,ydxdy \qquad (3.37)$$

$$f_3 = 2 \quad (a_3(x^2+y^2)+a_4) \quad (x,y)W(x,y)\,dxdy \qquad (3.38)$$

The final phase correction is given by

$$\phi(x,y) = \phi(x,y) - f_1 Z_1(x,y) - f_2 Z_2(x,y) - f_3 Z_3(x,y) - f_0 Z_0(x,y) \qquad (3.39)$$

For a discussion of least squares fitting of Zernike polynomials, see [Ref. 36].

16. PHVAR

The phase variance due to thermal blooming is computed by this subroutine using the residual phase screen provided by RESPHS. Normalized with respect to the aperture field, the variance is given by

$$\sigma^2 = \frac{U(x,y)\,\phi^2(x,y) + U(x,y)\,\phi(x,y)^{\,2}}{U(x,y)} \qquad (3.40)$$

TABLE XIV

PHVAR, RESPHS, and COEFS Program Variable Definitions

| Variable | Fortran Name Sub | Fortran Name Main | Definition |
|---|---|---|---|
| $\phi(x,y)$ | PH(i,j) | PH(i,j) | Phase array |
| | SIGSQO | SIGSQO | Phase variance |
| $a_0 - a_4$ | A1- A4 | - | Zernike coeffs. |
| $f_0 - f_3$ | PHMEAN<br>PHTILX<br>PHTILY<br>PHFOCUS | -<br>-<br>-<br>- | The expansion coefficients relative to a uniform weighting function |

17. AV

AV evaluates the path dependent part (second term) of the thermal blooming equation 3.30 . (see section PRIPHS) $\alpha(h)$ and $\sigma(h)$ are the absorption coefficient and scattering coefficient, respectively. $V_0$ is the user specified wind and $\omega$ is the slew rate. The denominator represents the total transverse wind component across the beam. $\theta$ is the zenith angle

and $\xi$ is the angle of attack of $V_0$ with respect to the beam. $V_0$ has been assumed to be opposite in direction and parallel to the target to transmitter LOS slew motion. Note also that $V_0$ will be applied as a constant the entire length of the beam path. This is discussed in chapter one.

TABLE XV

AV Program Variables and Definitions

| Variance | Fortran Name Sub | Main | Definition |
| --- | --- | --- | --- |
| $\alpha(h)+\sigma(h)$ | ALP | - | Total extinction coefficient |
| $\alpha(h)$ $(km)^{-1}$ | ALS | - | Absorption coeff. |
| $\sec(\theta)$ | SECCMG | SECCMG | secant of zenith angle |
| $V_0$ (m/sec) | VO | VO | Wind |
| | PHIDCT | PHIDCT | Slew rate |
| $h_{atm}$ (meters) | HATMC | HATMC | Height of the atmosphere |
| $h_t$ (meters) | HT | HTRANS | Height of the transmitter |

18. BLOOM

The purpose of BLOOM is to provide reasonable results for thermal blooming degradation when the Irel values are below approximately 0.3. In this region, the exponential Strehl relation predicts unacceptably severe results. Therefore, when the phase variance is greater than 1.2, BLOOM computes an Irel value based on GUTSMTF results. GUTSMTF is a full wave optics propagation code using FFTs.

Curve fit polynomials were developed using GUISMTF results for both a uniform and a truncated Gaussian aperture distribution. The resulting polynomials are

$$Irel = \frac{1}{-.08705 + 2.9148\sigma + .1723\sigma^2} \tag{3.41}$$

$$Irel = \frac{1}{1.2877 - 2.6491\sigma + 4.09603\sigma^2} \tag{3.42}$$

If the profile under consideration is a truncated Gaussian, i.e. the aperture diameter greater than the waist diameter of the beam, then the routine uses the truncated Gaussian polynomial. Otherwise, a combination of the two are used,

$$Irel_{tb} = \left[1-(d/b)^2\right] Irel_u + (d/b)^2 Irel_{tg} \tag{3.43}$$

where d is the aperture diameter and b is the waist diameter of the beam. [Ref. 37]

TABLE XVI

BLOOM Program Variables and Definitions

| Variable | Fortran Name Sub | Fortran Name Main | Definition |
|---|---|---|---|
| $\sigma^2$ | S | SIGSQ | Phase variance |
| $Irel_{tb}$ | T | TBLOOM | Total blooming produced Irel |
| $Irel_u$ | TRU | - | Curve fit Irel for uniform aperture dist. |
| $Irel_{tg}$ | TRG | - | Curve fit Irel for Gaussian aperture dist. |

19. MTFATM

MTFATM computes the atmospheric MTF and if specified, applies a tilt due to turbulence correction. The MTF is given by

$$M_t(\overline{\rho}) = \exp\left[-(\overline{\rho}/D)^{5/3}\left[1-d(\overline{\rho}/D)^{1/3}\right](D/\rho_0)^{5/3}\right] \qquad (3.44)$$

where D is the aperture diameter, $\rho_0$ is the coherence diameter and d is defined as 1-ADAP. ADAP is the fractional residual tilt due to turbulence and is a user specified parameter. If ADAP=0, M will represent the fully turbulence tilt corrected MTF. If ADAP=1, M will be the uncorrected MTF and may be written as

$$M_t(\overline{\rho}) = \exp\left[-(\overline{\rho}/\rho_0)^{5/3}\right] \qquad (3.45)$$

ADAP may be any value between 0 and 1.

TABLE XVII

MTFATM Program Variables and Definitions

| Variable | Fortran Name Sub | Main | Definition |
|---|---|---|---|
| $M_t(\overline{\rho})$ | F | F3 | Atmospheric MTF |
| $\rho_0$(meters) | RHO | RHO | Coherence dia. |
| D (meters) | D | DIA | Aperture dia. |

20. TRBREL

TRBREL computes the approximate Irel for a tilt corrected system. This value is used for comparison with the Irel produced by a prefect adaptive optics compensated system. The purpose of this comparison is to determine if noise will degrade the AO system to an extent as to make a full AO system undesirable. If this is the case, the program will apply tilt correction only to the beam.

21. FNDRHO

Subroutine FNDRHO calculates the coherence diameter that would result in the Irel value achieved by a perfect AO system. This is done by successive calls to subroutine TRBREI and iterating $\rho_0$. This new $\rho_0$ then becomes a factor in the AO compensation. Specifically it will be used by subroutine MTFATM to produce the atmospheric MTF of the AO corrected system.

TABLE XVIII

IRREL and FNDRHC Program Variables and Definitions

| Variable | Fortran Name Sub | Main | Definition |
|---|---|---|---|
| $M_t(\bar{\rho})$ | F2 | - | Atmospheric MTF |
| $M_a(\bar{\rho})$ | F1 | IRRMTF | Aperture MTF |
| Irel | EXD | EXD | Irel of perfect AO system |

22. TLTISO

The call to TLTISO is made when adaptive optics have not been user specified and isoplanatic calculations have not been inhibited. Also, if the signal to noise ratio at the AO sensor is such that the AO system will provide tilt correction only, TLTISO is called , again, provided isoplanatic calculations have not been inhibited.

The purpose of TLTISO is to include beam wander due to isoplanatism. The 2-sigma-p tilt is computed and combined with the jitter 2-sigma-p. This combined term is then used to compute the jitter MTF.

23. RELTOT

RELTOT simply averages the relative intensities due to a multiplicative and an RSS(root sum squared) approach to combining thermal blooming and the other propagation effects.

$$Irel = \frac{Irel_{rss} + Irel_m}{2} \qquad (3.46)$$

$Irel_m$ is the result of the multiplicative approach

$$Irel_m = Irel_{tb} * Irel_o \qquad (3.47)$$

where $Irel_{tb}$ is the Irel due to thermal blooming and $Irel_o$ is the Irel due to beam quality, jitter, turbulence , isoplanatism and adaptive optics effects. The RSS approach is given by

$$Irel_{rss} = \left[1 + \left(\frac{1}{Irel_o} - 1\right) + \left(\frac{1}{Irel_{tb}} - 1\right)\right]^{-1} \qquad (3.48)$$

TABLE XIX

RELTOT Program Variables and Definitions

| Variable | Fortran Name Sub | Fortran Name Main | Definition |
|---|---|---|---|
| $Irel_t$ | T | TTOTAL | Total Irel |
| $Irel_{rss}$ | TR | TRSS | Irel by RSS method |
| $Irel_m$ | TM | TMULT | Irel by multiplicative method |
| | EXD | EXD | Irel of perfect AO system |
| $Irel_o$ | - | TTRUE | Irel due to all other effects |
| $Irel_{tb}$ | - | TBLOOM | Irel due to thermal blooming |

24. ISOPLA

This routine calculates the MTF that characterizes the isoplanatic effect on the predictive or "look-ahead" adaptive optics system. The look-ahead angle is the major input parameter to this routine. The Fortran code was written by D.L. Fried [Ref. 38]. Fried developes the isoplanatic dependency of the AO system in terms of the effective antenna gain of the laser transmitter. The MTF that Fried formulates is given by

$$M_{iso}(\overline{\rho}) = \int^{\pi} 144.88 \cdot \lambda^{-2} \cdot \overline{\rho}^{-5/3} \cdot \sec(\theta) \cdot \mu(\nu \sec(\theta/\overline{\rho}), \phi)\, d\phi \qquad (3.49)$$

where

$$x = \nu \sec(\theta/\overline{\rho}) \qquad (3.50)$$

and

$$\mu(x,\phi) = \int C_n^2 \left\{ 1+(xh) \quad -\tfrac{1}{2}\left[1+2(xh)\cos\phi + (xh)^2\right]^{5/6} -\tfrac{1}{2}\left[1-2(xh)\cos + (xh)^2\right]^{5/6} \right\} dh \qquad (3.51)$$

$\theta$ is the zenith angle and $\nu$ is the target lead angle.

For detailed discussion of the theory and explicit development of the Fortran code, see [Ref. 39].

25. J0

J0 computes the zero order Bessel function based on the input argument. This routine is called by FARFLD in the calculation of the far-field irradiance.

## APPENDIX A

## GUTSAVG INPUT FILE

INPUT DATA FILE:

LASER: CO CW EDL 5P(9) TRANSITION 4.99210 MICRONS

CLIMATE: MID-LATITUDE SUMMER, CLEAR DAY

CASE: 1

| | | | |
|---|---|---|---|
| DIA | TELESCOPE DIAMETER | METERS | 0.150000E+01 |
| DIAOBS | CENTRAL OBSCURATION DIAMETER | METERS | 0.150000E+00 |
| BEAMSZ | GAUSSIAN WAIST THRU TELESCOPE | METERS | 0.100000E+02 |
| WAVE | CAVITY WAVELENGTH | METERS | 0.499210E-05 |
| PTOTAL | APERTURE TOTAL POWER | WATTS | 0.200000E+07 |
| THSEE | TURBULENCE SEEING | ARC-SEC | 0.0 |
| HGRND | HEIGHT OF GROUND ABOVE MSL | METERS | 0.300000E+03 |
| TDFLMT | TIMES DIFFRACTION LIMITED | - | 0.120000E+01 |
| WAVEEQ | RMS WAVES DISTORTION | - | 0.0 |
| SCALEQ | PHASE CORRELATION LENGTH | METERS | 0.300000E+00 |
| HTRANS | TRANSMITTER HEIGHT ABOVE MSL | METERS | 0.300000E+03 |
| HSAT | SATELLITE ALTITUDE | METERS | 0.100000E+07 |
| THETMX | MAXIMUM ZENITH ANGLE | DEGREES | 0.300000E+02 |
| LOFF | FLIGHT PATH OFFSET | METERS | 0.0 |
| RHOO | YURA'S TURB. COHERENCE DIA | METERS | 0.0 |
| VO | WIND VELOCITY | M/SEC | 0.600000E+01 |
| SIGJIT | 2-SIGMA-P JITTER | RADIANS | 0.500000E-05 |
| ADAP | FRAC. RESID. TURB. TILT | - | 0.100000E+01 |
| AOBLCM | BLOOMING CORRECTION (0-1) | - | 0.100000E+01 |
| AVGSPT | SPOT AVERAGINF FACTOR (0-1) | - | 0.100000E+01 |
| NFLAGC | INCLUDE CLOUDS MODEL | - | 0 |
| NFLAGA | USE FULL ZONAL A-C SYSTEM | - | 0 |
| NOISO | INHIBIT ISOPLANATIC CALCS | - | 1 |
| ABSLCZ | ZENITH TRANS FOR A-C SENSOR | - | 0.750000E+00 |
| XJT | TARGET RADIANT INTENSITY | W/STER | 0.250000E+03 |
| BWIDTH | A-C SYSTEM BANDWIDTH | HERTZ | 0.500000E+03 |
| NA | NUMBER OF A-C SYSTEM ACTUATORS | | 0.102400E+04 |
| N1 | NUMBER OF ANGLE INTERVALS | | 30 |
| N2 | ABSORPTION INTEGRATION INTERVALS | | 200 |
| N3 | TURBULENCE INTEGRATION INTERVALS | | 100 |
| N4 | MTF INTEGRATION INTERVALS | | 200 |
| N5 | THERMAL BLOOMING INTEGRATION INTERVALS | | 100 |

# APPENDIX B

## GUTSAVG OUTPUT FILE

| | | | |
|---|---|---|---|
| LASER: | CO CW EDL 5P(9) TRANSITION | | 4.99210 MICRONS |
| CLIMATE: | MID-LATITUDE SUMMER, CLEAR DAY | | |
| CASE: | 1 | | |
| DIA | TELESCOPE DIAMETER | METERS | .150E+01 |
| DIAOBS | CENTRAL OBSCURATION DIAMETER | METERS | .150E+00 |
| BEAMSZ | GAUSSIAN WAIST THRU TELESCOPE | METERS | .100E+02 |
| WAVE | CAVITY WAVELENGTH | METERS | .499210E-05 |
| PTOTAL | APERTURE TOTAL POWER | WATTS | .200E+07 |
| THSEE | TURBULENCE SEEING | ARC-SEC | .000E+00 |
| HGRND | HEIGHT OF GROUND ABOVE MSL | METERS | .300E+03 |
| TDPLMT | TIMES DIFFRACTION LIMITED | - | .120E+01 |
| WAVERQ | RMS WAVES DISTORTION | - | .000E+00 |
| SCALEQ | PHASE CORRELATION LENGTH | METERS | .300E+00 |
| HTRANS | TRANSMITTER HEIGHT ABOVE MSL | METERS | .300E+03 |
| HSAT | SATELLITE ALTITUDE | METERS | .100E+07 |
| THETMX | MAXIMUM ZENITH ANGLE | DEGREES | .300E+02 |
| LOFF | FLIGHT PATH OFFSET | METERS | .000E+00 |
| RHO0 | YURA'S TURB. COHERENCE DIA | METERS | .000E+00 |
| V0 | WIND VELOCITY | M/SEC | .060E+02 |
| SIGJIT | 2-SIGMA-P JITTER | RADIANS | .500E-05 |
| ADAP | FRAC. RESID. TURB. TILT | - | .100E+01 |
| AOBLCM | BLOOMING CORRECTION (0-1) | - | .100E+01 |
| AVGSPT | SPOT AVERAGING FACTOR (0-1) | - | .100E+01 |
| NFLAGA | USE FULL ZONAL A-O SYSTEM | - | 0 |
| NOISC | INHIBIT ISOPLANATIC CALCS | - | 1 |
| ABSLCZ | ZENITH TRANS FOR A-O SENSOR | - | .750E+00 |
| XJT | TARGET RADIANT INTENSITY | W/STER | .250E+03 |
| BWIDTH | A-O SYSTEM BANDWIDTH | HERTZ | .500E+03 |
| NA | NUMBER OF A-O SYSTEM ACTUATORS | | 1024. |
| N1 | NUMBER OF ANGLE INTERVALS | | 30 |
| N2 | ABSORPTION INTEGRATION INTERVALS | | 200 |
| N3 | TURBULENCE INTEGRATION INTERVALS | | 100 |
| N4 | MTF INTEGRATION INTERVALS | | 200 |
| N5 | THERMAL BLOOMING INTEGRATION INTERVALS | | 100 |

PATH ANALYSIS RESULTS:

| STEP NO. | RANGE (KM) | SLEW (MRAD/SEC) | OMEGA (DEG) | TIME (SEC) | ATMOS. TRANSMISSION SCAT | ABSORP | RHO (CM) |
|---|---|---|---|---|---|---|---|
| 1. | 999.738 | 7.1582 | 1.08 | 2.63 | 0.99802 | 0.53314 | 51.1 |
| 2. | 1000.045 | 7.1541 | 2.16 | 5.27 | 0.99802 | 0.53302 | 51.0 |
| 3. | 1000.659 | 7.1459 | 3.24 | 7.90 | 0.99802 | 0.53278 | 51.0 |
| 4. | 1001.579 | 7.1337 | 4.31 | 10.53 | 0.99802 | 0.53242 | 51.0 |
| 5. | 1002.805 | 7.1175 | 5.39 | 13.16 | 0.99801 | 0.53195 | 50.9 |
| 6. | 1004.334 | 7.0973 | 6.46 | 15.80 | 0.99801 | 0.53135 | 50.9 |
| 7. | 1006.167 | 7.0732 | 7.52 | 18.43 | 0.99800 | 0.53064 | 50.8 |
| 8. | 1008.301 | 7.0453 | 8.59 | 21.06 | 0.99800 | 0.52982 | 50.8 |
| 9. | 1010.735 | 7.0138 | 9.65 | 23.70 | 0.99799 | 0.52888 | 50.7 |
| 10. | 1013.465 | 6.9786 | 10.70 | 26.33 | 0.99799 | 0.52782 | 50.6 |
| 11. | 1016.490 | 6.9400 | 11.74 | 28.96 | 0.99798 | 0.52665 | 50.5 |
| 12. | 1019.806 | 6.8981 | 12.79 | 31.59 | 0.99797 | 0.52537 | 50.4 |
| 13. | 1023.413 | 6.8530 | 13.82 | 34.23 | 0.99796 | 0.52398 | 50.2 |
| 14. | 1027.305 | 6.8048 | 14.85 | 36.86 | 0.99796 | 0.52248 | 50.1 |
| 15. | 1031.481 | 6.7537 | 15.86 | 39.49 | 0.99795 | 0.52088 | 50.0 |
| 16. | 1035.935 | 6.6999 | 16.87 | 42.13 | 0.99794 | 0.51917 | 49.8 |
| 17. | 1040.666 | 6.6435 | 17.88 | 44.76 | 0.99792 | 0.51735 | 49.6 |
| 18. | 1045.668 | 6.5847 | 18.87 | 47.39 | 0.99791 | 0.51544 | 49.5 |
| 19. | 1050.939 | 6.5237 | 19.85 | 50.02 | 0.99790 | 0.51342 | 49.3 |
| 20. | 1056.474 | 6.4606 | 20.83 | 52.66 | 0.99789 | 0.51130 | 49.1 |
| 21. | 1062.269 | 6.3955 | 21.79 | 55.29 | 0.99787 | 0.50909 | 48.9 |
| 22. | 1068.319 | 6.3288 | 22.75 | 57.92 | 0.99786 | 0.50679 | 48.7 |
| 23. | 1074.621 | 6.2604 | 23.69 | 60.56 | 0.99785 | 0.50439 | 48.5 |
| 24. | 1081.169 | 6.1907 | 24.63 | 63.19 | 0.99783 | 0.50191 | 48.3 |
| 25. | 1087.959 | 6.1196 | 25.55 | 65.82 | 0.99781 | 0.49933 | 48.1 |
| 26. | 1094.988 | 6.0475 | 26.46 | 68.45 | 0.99780 | 0.49668 | 47.9 |
| 27. | 1102.250 | 5.9744 | 27.36 | 71.09 | 0.99778 | 0.49393 | 47.7 |
| 28. | 1109.740 | 5.9006 | 28.25 | 73.72 | 0.99776 | 0.49111 | 47.4 |
| 29. | 1117.455 | 5.8260 | 29.13 | 76.35 | 0.99774 | 0.48821 | 47.2 |
| 30. | 1125.388 | 5.7510 | 30.00 | 78.99 | 0.99772 | 0.48524 | 47.0 |

TRANSMISSION ANALYSIS OUTPUT:

| STEP | TRANSMISSION COEFFICIENTS DUE TO SPREADING | AMP LOSS WITH AO | THERMAL BLOOMING | RANGE SCALE | MAX IRRAD (KW/CM2) | FLUENCE (KJ/CM2) |
|---|---|---|---|---|---|---|
| 1. | 0.11826 | 1.00000 | 0.01522 | 0.9999 | 0.5779E-04 | 0.1522E-03 |
| 2. | 0.11824 | 1.00000 | 0.01521 | 0.9993 | 0.5770E-04 | 0.3041E-03 |
| 3. | 0.11821 | 1.00000 | 0.01518 | 0.9981 | 0.5753E-04 | 0.4555E-03 |
| 4. | 0.11817 | 1.00000 | 0.01515 | 0.9963 | 0.5726E-04 | 0.6063E-03 |
| 5. | 0.11810 | 1.00000 | 0.01511 | 0.9938 | 0.5692E-04 | 0.7562E-03 |
| 6. | 0.11802 | 1.00000 | 0.01505 | 0.9908 | 0.5649E-04 | 0.9049E-03 |
| 7. | 0.11793 | 1.00000 | 0.01499 | 0.9872 | 0.5597E-04 | 0.1052E-02 |
| 8. | 0.11782 | 1.00000 | 0.01491 | 0.9830 | 0.5539E-04 | 0.1198E-02 |
| 9. | 0.11770 | 1.00000 | 0.01483 | 0.9783 | 0.5472E-04 | 0.1342E-02 |
| 10. | 0.11756 | 1.00000 | 0.01473 | 0.9730 | 0.5399E-04 | 0.1484E-02 |
| 11. | 0.11740 | 1.00000 | 0.01463 | 0.9672 | 0.5320E-04 | 0.1624E-02 |
| 12. | 0.11724 | 1.00000 | 0.01452 | 0.9610 | 0.5234E-04 | 0.1762E-02 |
| 13. | 0.11705 | 1.00000 | 0.01440 | 0.9542 | 0.5142E-04 | 0.1898E-02 |
| 14. | 0.11686 | 1.00000 | 0.01427 | 0.9470 | 0.5046E-04 | 0.2030E-02 |
| 15. | 0.11664 | 1.00000 | 0.01414 | 0.9393 | 0.4945E-04 | 0.2161E-02 |
| 16. | 0.11642 | 1.00000 | 0.01400 | 0.9313 | 0.4839E-04 | 0.2288E-02 |
| 17. | 0.11618 | 1.00000 | 0.01385 | 0.9228 | 0.4730E-04 | 0.2413E-02 |
| 18. | 0.11593 | 1.00000 | 0.01369 | 0.9140 | 0.4618E-04 | 0.2534E-02 |
| 19. | 0.11566 | 1.00000 | 0.01354 | 0.9049 | 0.4504E-04 | 0.2653E-02 |
| 20. | 0.11538 | 1.00000 | 0.01337 | 0.8954 | 0.4387E-04 | 0.2768E-02 |
| 21. | 0.11509 | 1.00000 | 0.01320 | 0.8857 | 0.4268E-04 | 0.2881E-02 |
| 22. | 0.11479 | 1.00000 | 0.01303 | 0.8757 | 0.4148E-04 | 0.2990E-02 |
| 23. | 0.11448 | 1.00000 | 0.01286 | 0.8654 | 0.4028E-04 | 0.3096E-02 |
| 24. | 0.11415 | 1.00000 | 0.01268 | 0.8550 | 0.3907E-04 | 0.3199E-02 |
| 25. | 0.11381 | 1.00000 | 0.01250 | 0.8443 | 0.3786E-04 | 0.3298E-02 |
| 26. | 0.11346 | 1.00000 | 0.01232 | 0.8335 | 0.3665E-04 | 0.3395E-02 |
| 27. | 0.11310 | 1.00000 | 0.01213 | 0.8226 | 0.3545E-04 | 0.3488E-02 |
| 28. | 0.11273 | 1.00000 | 0.01195 | 0.8115 | 0.3427E-04 | 0.3578E-02 |
| 29. | 0.11235 | 1.00000 | 0.01176 | 0.8003 | 0.3309E-04 | 0.3666E-02 |
| 30. | 0.11196 | 1.00000 | 0.01158 | 0.7891 | 0.3193E-04 | 0.3750E-02 |

```
CASE DATA AND CALCULATED FACTORS:

TRANSMITTER DIAMETER       =     150.00 CM
CAVITY WAVELENGTH          =   4.992100 UM
APERTURE TOTAL POWER       =     2.0000 MW
TIMES DIFFRACTION LIMIT    =       1.20
(WIDE ANGLE SCATTERING)
TRANSMITTER ALTITUDE       =     300.00 M
SATELLITE ALTITUDE         =    1000.00 KM
MAX ZENITH ANGLE           =      30.00 DEG
FLIGHT PATH OFFSET         =       0.0  KM
RHOO                       = 0.5105E+02 CM
WIND VELOCITY  .           =       6.00 M/SEC
HEIGHT OF GROUND           =     300.00 M
OPT SEEING AT 5500A        =   0.15E+01 ARC-SEC

BLOOMING ADAPTIVE OPTICS FACTOR  = 0.1000E+01
IRRADIANCE AREA AVERAGING FACTOR = 0.1000E+01

TELESCOPE DIMENSIONS:
OUTER DIAMETER           =     150.00 CM
INNER DIAMETER           =      15.00 CM
GAUSSIAN WAIST DIAMETER  =    1000.00 CM

RMS WAVES DISTORTION         = 0.1031E+00
PHASE CORRELIATION LENGTH = 0.3000E+02 CM

FOR THE FULL ZONAL A-C MODEL:
  ZENITH TRANS. AT A-C SENSOR    = 0.7500E+00
  TARGET RADIANT INTENSITY       = 0.2500E+03 W/STER
  ADAPTIVE OPTICS BANDWIDTH      = 0.5000E+03 HERTZ
  NUMBER OF ACTUATORS          =        1024.

THIS RUN -
  IS THE BASIC CODE WITH ONLY SOME MEASURE OF TILT CORRECTION
  AND WITHOUT AN ISOPLANATIC MODEL

NUMBER OF INTERVAL STEPS FOR:
  ANGULAR INTERVAL                 =          30
  ABSORPTION INTEGRATION           =         200
  RHO CALCULATION                  =         100
  MTF CALCULATION                  =         200
  THERMAL BLOOMING                 =         100

ZENITH LOG AMPLITUDE VARIANCE =  0.4905E-02
RELATIVE IRRADIANCE REDUCTION =  0.9951E+00

ZENITH LOOK-AHEAD ANGLE        = 0.5227E+02 URAD

ISOPLANATIC JITTER (2-SIGMA-P) = 0.2004E+07

2-SIGMA-P BEAM JITTER          =       5.00 URAD
TURBULENCE JITTER REJECTION    = 0.1000E+01
(RESIDUAL = INITAL * ADAP)


======== PROPAGATION RESULTS =======
INTEGRATED FLUX ON TARGET      =          0.007499 KJ/CM2
TOTAL ILLUMINATION TIME        =            157.97 SEC
```

## APPENDIX C

## GUTSAVG PROGRAM LISTING

```
C*******************************************************************************
C                                                                              *
C  GUTSAVG        NAVAL POSTGRADUATE SCHOOL VERSION 1.2                         *
C                                                                              *
C  MODIFICATION 1.2                                                             *
C                                                                              *
C  LATEST CHANGE DATE 22 FEB 84                                                 *
C                                                                              *
C  THIS VERSION OF GUTSAVG HAS BEEN MODIFIED FOR IBM 370/360                   *
C  COMPATABILITY. VARIABLE NAME LENGTHS HAVE BEEN CHANGED AND                   *
C  APPROAPRIATE FORTRAN CHANGES MADE. MACHINE GENERATED ERRORS MAY             *
C  STILL OCCUR DUE TO UNRESOLVED CDC/IBM DIFFERENCES                           *
C
C  THE CLOUD MODEL HAS BEEN REMOVED FROM THIS VERSION
C
C
C*******************************************************************************
C
C============== MEMORY ALLOCATION AND VARIABLE  ASSIGNMENTS ===========C
C
      REAL BQMTF(300)
      REAL JITMTF(300)
      REAL A(100,14)
      REAL B(15)
      REAL PH(101,201)
      REAL TISC(300)
      REAL LOFF,MU
      REAL IRRMTF(300)
      REAL LY,IZ
      REAL NASCRT,NU,ISCANG,ISOANO,NA
C
      INTEGER TITLE1(80),TITLE2(80),TITLE3(80)
      INTEGER DESCR(40,80)
C
      COMMON /ATMO/ HATMO
      COMMON /EQ/ IDFLMT,VARBQ,WAVEEQ,SCALEQ
      COMMON /ABBFLD/ DIA,DIAOBS,BEAMSZ,U0
C
C============== CONSTANTS ASSIGNMENTS =================================C
C
      ML=201
      JJ=0
      TSTOLD=0.
      F4=1
      PI=2.*ARSIN(1.)
      MLH=ML/2+1
      HATMO=3.E4
      TAU=0.
      XMW=1.E+6
      XCM=1.E+2
      XKW=1.E-3
      XK2=1.E-7
      RTD=90./ARSIN(1.)
      REARTH=6.4E6
      MU=3.986E14
      THETSP=2.*PI/(24.*3600.)
      VSURF=REARTH*THETSP
C
      CALL ERRSET (208,256,-1,1,1)
C
C============== DATA INPUT SECTOR =====================================C
C
      READ (5,530)  (TITLE1(I),I=1,80)
      READ (5,530)  (TITLE2(I),I=1,80)
      READ (5,530)  (TITLE3(I),I=1,80)
C
      READ (5,510)  (DESCR(1,II),II=1,50),  DIA
      READ (5,510)  (DESCR(2,II),II=1,50),  DIAOBS
      READ (5,510)  (DESCR(3,II),II=1,50),  BEAMSZ
      READ (5,510)  (DESCR(4,II),II=1,50),  WAVE
      READ (5,510)  (DESCR(5,II),II=1,50),  PTOTAL
      READ (5,510)  (DESCR(6,II),II=1,50),  THSEE
      READ (5,510)  (DESCR(7,II),II=1,50),  BGRND
C
C-------------------------------------------------------------------------
C      (EITHER IDFLMT OR WAVEBQ MUST BE DEFINED, BUT NOT BOTH)
```

```
C-----------------------------------------------------------------------
C
      READ (5,510) (DESCR(8,II),II=1,50), TDFLMT
      READ (5,510) (DESCR(9,II),II=1,50), WAVEBQ
      READ (5,510) (DESCR(10,II),II=1,50), SCALBQ
      READ (5,510) (DESCR(11,II),II=1,50), HTRANS
      READ (5,510) (DESCR(12,II),II=1,50), HSAT
      READ (5,510) (DESCR(13,II),II=1,50), THETMX
      READ (5,510) (DESCR(14,II),II=1,50), LOFF
      READ (5,510) (DESCR(15,II),II=1,50), RHCO
      READ (5,510) (DESCR(16,II),II=1,50), VO
      READ (5,510) (DESCR(17,II),II=1,50), SIGJIT
      READ (5,510) (DESCR(18,II),II=1,50), ADAP
      READ (5,510) (DESCR(19,II),II=1,50), AOBLOM
      READ (5,510) (DESCR(20,II),II=1,50), AVGSPT
      READ (5,520) (DESCR(21,II),II=1,50), NFLAGA
      READ (5,520) (DESCR(22,II),II=1,50), NOISO
C
C-----------------------------------------------------------------------
C     IF FULL AC CORRECTION IS NOT USED, THE following
C     PARAMETERS ARE NOT REALLY USED. ONLY BWIDTH
C     HAS AN EFFECT, it CAUSES the LOOK AHEAD ANGLE TO
C     BE LARGER BY TAU*PHIDOT.
C-----------------------------------------------------------------------
C
      READ (5,510) (DESCR(23,II),II=1,50), ABSLOZ
      READ (5,510) (DESCR(24,II),II=1,50), XJT
      READ (5,510) (DESCR(25,II),II=1,50), BWIDTH
      READ (5,510) (DESCR(26,II),II=1,50), NA
C
C-----------------------------------------------------------------------
C     ITERATION LOOP LIMITS:
C     N1 NUMBER OF SUBTHETA INTERVALS FROM 0 TO THETMX
C     N2 NUMBER OF INTEGRATION INTERVALS FOR ABSORPTION
C     N3 NUMBER OF INTEGRATION INTERVALS FOR TURBULENCE
C     N4 NUMBER OF INTEGRATION INTERVALS FOR MTF
C     N5 NUMBER OF SUBINTERVALS USED FOR SLANT PATH UPDATE FOR
C     THERMAL BLOOMING
C-----------------------------------------------------------------------
C
      READ (5,520) (DESCR(27,II),II=1,50), N1
      READ (5,520) (DESCR(28,II),II=1,50), N2
      READ (5,520) (DESCR(29,II),II=1,50), N3
      READ (5,520) (DESCR(30,II),II=1,50), N4
      READ (5,520) (DESCR(31,II),II=1,50), N5
C
C============= ECHO CHECK OUTPUT SECTOR ================================C
C
      WRITE (6,190)
      WRITE (6,195) (TITLE1(I),I=1,80)
      WRITE (6,195) (TITLE2(I),I=1,80)
      WRITE (6,195) (TITLE3(I),I=1,80)
      WRITE (6,180) (DESCR(1,II),II=1,50), DIA
      WRITE (6,180) (DESCR(2,II),II=1,50), DIAOBS
      WRITE (6,180) (DESCR(3,II),II=1,50), BEAMSZ
      WRITE (6,180) (DESCR(4,II),II=1,50), WAVE
      WRITE (6,180) (DESCR(5,II),II=1,50), PTOTAL
      WRITE (6,180) (DESCR(6,II),II=1,50), THSEE
      WRITE (6,180) (DESCR(7,II),II=1,50), HGBND
      WRITE (6,180) (DESCR(8,II),II=1,50), TDFLMT
      WRITE (6,180) (DESCR(9,II),II=1,50), WAVEBQ
      WRITE (6,180) (DESCR(10,II),II=1,50), SCALBQ
      WRITE (6,180) (DESCR(11,II),II=1,50), HTRANS
      WRITE (6,180) (DESCR(12,II),II=1,50), HSAT
      WRITE (6,180) (DESCR(13,II),II=1,50), THETMX
      WRITE (6,180) (DESCR(14,II),II=1,50), LOFF
      WRITE (6,180) (DESCR(15,II),II=1,50), RHCO
      WRITE (6,180) (DESCR(16,II),II=1,50), VO
      WRITE (6,180) (DESCR(17,II),II=1,50), SIGJIT
      WRITE (6,180) (DESCR(18,II),II=1,50), ADAP
      WRITE (6,180) (DESCR(19,II),II=1,50), AOBLOM
      WRITE (6,180) (DESCR(20,II),II=1,50), AVGSPT
      WRITE (6,185) (DESCR(21,II),II=1,50), NFLAGA
      WRITE (6,185) (DESCR(22,II),II=1,50), NOISO
      WRITE (6,180) (DESCR(23,II),II=1,50), ABSLOZ
      WRITE (6,180) (DESCR(24,II),II=1,50), XJT
```

```
      WRITE (6,180) (DESCR(25,II),II=1,50), BWIDTH
      WRITE (6,180) (DESCR(26,II),II=1,50), NA
      WRITE (6,185) (DESCR(27,II),II=1,50), N1
      WRITE (6,185) (DESCR(28,II),II=1,50), N2
      WRITE (6,185) (DESCR(29,II),II=1,50), N3
      WRITE (6,185) (DESCR(30,II),II=1,50), N4
      WRITE (6,185) (DESCR(31,II),II=1,50), N5
C
C=============== DATA REALIGNMENT SECTOR ===============================C
C
      IF (SCALBQ.EQ.0.) SCALBQ=DIA/5.
      IF (WAVEBQ.NE.0.) VARBQ=(2.*PI*WAVEBQ)**2
      SGJITO=SIGJIT
      IF (NFLAGA.EQ.1) ADAP=0.
      IF (NOISC.EQ.1) ISOANO=1.E10
      NASQRT=SQRT(NA)
      LOGABS=-ALOG(ABSLC2)
      TAU=1./BWIDTH/PI
C
C============== INITIAL CALCULATIONS SECTOR ============================C
C
      IF (RHOO.EQ.0..AND.THSEE.NE.0.) RHOO=(WAVE/.55E-6)**1.2*(.054/THSEE
     1)
      THETMX=THETMX/RTD
      HSATD=HSAT-HTRANS
      HABVGD=HTRANS-HGRND
      IF (HABVGD.LT.0.) HABVGD=0.
C
      R=REARTH+HTRANS
      RS=REARTH+HSAT
      NFLGSN=0
C
C-----------------------------------------------------------------------
C     COMPUTE EARTH CENTER ANGLE OFF-SET
C-----------------------------------------------------------------------
C
      ANGOFF=LOFF/R
      A2=ANGOFF/2.
C
C-----------------------------------------------------------------------
C     COMPUTE COORDINATE TRANSLATIONS DUE TO OFF-SET
C-----------------------------------------------------------------------
C
      LY=+2.*R*SIN(A2)*COS(A2)
      LZ=2.*R*SIN(A2)**2
C
C-----------------------------------------------------------------------
C     COMPUTE EARTH CENTER ANGULAR RATE
C-----------------------------------------------------------------------
C
      THETDT=SQRT(MU/RS**3)
C
C-----------------------------------------------------------------------
C     COMPUTE ORBITAL SPEED
C-----------------------------------------------------------------------
C
      VSAT=THETDT*RS
C
C-----------------------------------------------------------------------
C     ADJUST INTENTANEOUS SLEWRATE FOR ROTATION OF EARTH,
C     assuming both are colinear.
C-----------------------------------------------------------------------
C
      THETDT=ABS(THETDT-THETSF)
C
C-----------------------------------------------------------------------
C     COMPUTE VELOCITY OF SATELLITE RELATIVE TO THE TRANSMITTER SITE
C-----------------------------------------------------------------------
C
      VS=THETDT*RS
C
C-----------------------------------------------------------------------
C     COMPUTE INITIAL LIMITS ON THE TIME AND ANGLE EARTH CENTER
C     .for an or line flight path
C-----------------------------------------------------------------------
C
```

```
      ECANG=ARCOS(R*SIN(THETMX)/RS)+THETMX-PI/2.
      TIMEX2=ECANG/THETDT
      TIMTOT=2.*TIMEX2
      DTIME=TIMEX2/N1
C
C------------------------------------------------------------------------
C     IF SATELITE ALTITITUDE IS AN THE ORDER OF THE RADIUS OF
C     THE earth, gutsfp (footprint)  WORKS BETTER BY SETTING
C     the time step instead of the angle step
C------------------------------------------------------------------------
C
      IF (HSAT.GT.REARTH/2.) DTIME=10.
C
C------------------------------------------------------------------------
C     COMPUTE VACUUM IRRADIANCE AND APERTURE MTF.  NOTE THAT THE
C     POINT SPACING HERE MUST BE THE SAME AS USED IN THE MTF
C     INTEGRATION BELOW.   HENCE WE DEFINE DX NOW.
C------------------------------------------------------------------------
C
      DX=DIA/N4
C
C------------------------------------------------------------------------
C     THE CALL TO UOCST DETERMINES THE CONSTANT THAT MAKES THE EXIT
C     APERTURE POWER PTOTAL.
C------------------------------------------------------------------------
C
      CALL UOCST (PTOTAL,M1)
      CALL FARFLD (DX,TISC,IRRMTF,M1,N4,HSATD,WAVE,PTOTAL,PMAXO)
C
C------------------------------------------------------------------------
C     IF THE WAVEBQ IS NOT SPECIFIED AS INPUT, COMPUTE ON BASIS OF
C     TDFLMT.
C------------------------------------------------------------------------
C
      IF (WAVEBQ.EQ.0.) CALL DETWAV (IRRMTF,DX,N4)
C
C------------------------------------------------------------------------
C     IF TDFLMT WAS NOT SPECIFIED, COMPUTE IT .
C------------------------------------------------------------------------
C
      IF (TDFLMT.NE.0.) GO TO 10
      CALL BQIBEL (IRRMTF,N4,DX,TBQ)
      TDFLMT=SQRT(1./TBQ)
10    CONTINUE
C
C------------------------------------------------------------------------
C     DEFINE BEAM QUALITY MTF ARRAY.
C------------------------------------------------------------------------
C
      CALL BM (BQMTF,DX,N4)
C
C------------------------------------------------------------------------
C     DEFINE JITTER MTF ARRAY.
C------------------------------------------------------------------------
C
      CALL JIT (JITMTF,DX,N4,SGJITC,WAVE)
C
C------------------------------------------------------------------------
C     COMPUTE ZENITH ABSORPTION, SCATTERING, AND RHOO VALUES.
C------------------------------------------------------------------------
C
      CALL ABSORB (N2,HTRANS,TABSO)
      CALL SCAT (N2,HTRANS,TSCATO)
      IF (RHOO.EQ.0.) CALL RHOTRB (N3,HTRANS,HABVGD,WAVE,RHOO)
C
C------------------------------------------------------------------------
C     DEFINE SEEING AT 5500A
C------------------------------------------------------------------------
C
      THSEE=(WAVE/.55E-6)**1.2*(.054/RHOO)
C
      IF (NPLAGA.GE.1.AND.NOISO.EQ.0) CALL ISCTRB (N3,HTRANS,HABVGD,WAVE
     1,ISOANO)
C
C------------------------------------------------------------------------
C     CALCULATE LOG AMPLITUDE SCINTILLATION FOR ZENITH ANGLE.
```

```
C-----------------------------------------------------------------------
C
      CALL SCINT (SIGX2,N3,HTRANS,HGND,WAVE)
C
C-----------------------------------------------------------------------
C     COMPUTE THE THERMAL BLOOMING PHASE DISTORTION THAT does not depend
C     SLANT PATH CHARACTERISTICS
C-----------------------------------------------------------------------
C
      CALL PRTPHS (MI,MLH,WAVE,PH)
      CALL RESPHS (MI,MLH,PH)
      CALL PHVAR (MI,MLH,PTOTAL,PH,SIGSQ0)
C
C-----------------------------------------------------------------------
C     INITIALIZE ACCUMULATED FLUENCE TO ZERO
C-----------------------------------------------------------------------
C
      FLUX=0.
C
C-----------------------------------------------------------------------
C     SET SNR FLAG TO OFF
C-----------------------------------------------------------------------
C
      NFLGSN=0
C
C
C*************** M A I N    P R O G R A M    L O O P *****************C
C
C-----------------------------------------------------------------------
C     LOOP ON IRRADIANCES AND ACCUMULATED FLUENCES FOR A FIXED LOFF
C-----------------------------------------------------------------------
C
      DO 120 I=1,N1
C
C-----------------------------------------------------------------------
C     COMPUTE TOTAL LENGTH OF ILLUMINATION TIME FROM (+,-)
C     OVER PASS ANGLE
C     THIS IS THE TOTAL TIME.  WE USE HALF OF THIS TO DETERMINE THE
C     FUNCTION EVALUATION ANGLE.
C-----------------------------------------------------------------------
C
      TIME=2.*((I-1)*DTIME+DTIME/2.)
C
C-----------------------------------------------------------------------
C     COMPUTE EARTH CENTER ANGLE AT ON LINE COORDINATES AND TIME/2.
C     THIS ANGLE IS TO THE MID-POINT OF THE INTEGRATION INTERVAL.
C     THE ANGLE ECANGF,COMPUTED LATER, IS TO THE UPPER LIMIT OF THE
C     integration limit.
C
C****** THE COMMENTED ECANG SHOULD BE USED WHEN IT IS DESIRED THAT
C       THE INTEGRATION SHOULD START AT THE LOW POINT AND INCREASE
C       TOWARDS THE ZENITH.  THE CURRENT CALCULATION STARTS AT
C       THE ZENITH AND GOES DOWN.
C-----------------------------------------------------------------------
C
C***  ECANG=(TIMTOT-TIME)/2.*THETDT
C
      ECANG=TIME/2.*THETDT
C
C
C-----------------------------------------------------------------------
C     COMPUTE TARGET COORDINATES
C-----------------------------------------------------------------------
C
      X0=RS*SIN(ECANG)
      Z0=RS*COS(ECANG)
      X=X0
      Y=LY*COS(ANGOFF)+(Z0-R+LZ)*SIN(ANGOFF)
      Z=-LY*SIN(ANGOFF)+(Z0-R+LZ)*COS(ANGOFF)
C
C-----------------------------------------------------------------------
C     COMPUTE ON LINE OF SIGHT ANGLE OF SAT.
C     THIS ANGLE IS NOT USED AT PRESENT .   IT IS THE ANGLE OF THE
C     SAT AS MEASURED FROM A POINT UNDER THE GROUND TRACK .
C-----------------------------------------------------------------------
C
      THETA=ATAN(RS*SIN(ECANG)/(RS*COS(ECANG)-R))
```

```
C
C-----------------------------------------------------------------------
C     COMPUTE RANGE TC TARGET
C-----------------------------------------------------------------------
C
      RANGE=SQRT(X**2+Y**2+Z**2)
C
C-----------------------------------------------------------------------
C     INSTANTANEOUS SLEW RATE
C-----------------------------------------------------------------------
C
      VX=VS*COS(ECANG)
      VY=-VS*SIN(ECANG)*SIN(ANGOFF)
      VZ=-VS*SIN(ECANG)*CCS(ANGOFF)
      WX=Y*VZ-Z*VY
      WY=Z*VX-X*VZ
      WZ=X*VY-Y*VX
C
      PHIDOT=SQRT(WX**2+WY**2+WZ**2)/RANGE**2
C
C-----------------------------------------------------------------------
C     COMPUTE ANGLE FRCM ZENITH
C
C     OMEGA EQUALS ANGLE DCWN FROM ZENITH
C     OMWIND EQUALS ANGLE CF WIND ATTACK TC LCS IF TARGET
C     MOTION AND WIND ARE COPLANAR.
C-----------------------------------------------------------------------
C
      OMEGA=ARCCS(Z/RANGE)
      OMWIND=ARSIN(X/RANGE)
C
      COSOMG=CCS(OMEGA)
      SECOMG=1./COSCMG
      COSWND=CCS(OMWIND)
C
C-----------------------------------------------------------------------
C     ADJUST FCR SLANT PATH, BLOOMING LOSS, ABSCRPTION LOSS, SCATTERING
C     LCSS, AND TURBULENCE RHO
C
C-----------------------------------------------------------------------
C
C
      CALL AV (N5,VC,PHIDCT,HTRANS,CCSWND,cosomg,E)
      SIGSQ=SIGSQ0*E
C
C-----------------------------------------------------------------------
C     APPLY THERMAL BLCCMING
C     ADAPTIVE OPTICS DEGREE OF COMPENSATION
C-----------------------------------------------------------------------
C
      SIGSQ=SIGSQ*ACBICE
C
      SIG=SQRT(SIGSQ)
      TBLOOM=EXP(-SIGSQ)
      IF (SIGSQ.GT.1.2) CALL BLOOM (DIA,BEAMSZ,SIGSQ,TBLOOM)
      TABS=TABS0**SECCMG
      TSCAT=TSCAT0**SECCMG
      RHC=RHO0*COSCMG**(.6)
C
C-----------------------------------------------------------------------
C COMPUTE LOOK AHEAD ANGLE ASSUMING EARTH ROTATION AND SATELLITE MOTION
C ARE IN THE SAME DIRECTION.
C-----------------------------------------------------------------------
C
      TWCT=RANGE*2./3.E8
      DRT=TWOT*(ABS(VSAT-VSURF))
      PRCJAN=ARCOS(X/RANGE)
      PRCJ=DRT*SIN(PRCJAN)
      NU=PROJ/RANGE+TAU*PHIDOT
      IF (I.EQ.1) ZENNU=NU
C
C-----------------------------------------------------------------------
C     IF executed, the following is a full ao simulation
C-----------------------------------------------------------------------
C
      IF (NFLAGA.EQ.C) GC TC 40
```

```
C
C-----------------------------------------------------------------------
C     MCDIFY RHC FCR EFFECT OF ADAPTIVE OPTICS
C-----------------------------------------------------------------------
C
      RHCLD=RHC
      RHOU=RHO
      R0=2.1*RHC
C
C-----------------------------------------------------------------------
C     DETERMINE APPRCXIMATE I-REL TC SEE IF AC SHOULD BE USED,
C     given PRESENt NOISE.
C-----------------------------------------------------------------------
C
      DCR=DIA/RHO
      CALL TRBREL (IRRMTF,DIA,N4,DX,EXDTST,RHC)
C
C-----------------------------------------------------------------------
C     COMPUTE RESIDUAL VARIANCE DUE TO PERFECT ADAPTIVE OPTICS,
C     INFINITE BANDWIDTH, AND FINITE NUMBER OF ACTUATORS.
C-----------------------------------------------------------------------
C
      D1=.320*(DIA/R0/NASQRT)**(1.6667)
      TES=LOGABS*SECCMG
      TSENSR=EXP(-TES)
C
C-----------------------------------------------------------------------
C     DETERMINE PHASE VARIANCE ASSOCIATED WITH SENSOR.
C-----------------------------------------------------------------------
C
      PHSERR=8.5E-6*BWIDTH*NA**2*(RANGE/5.E5*2.5/DIA)**4*(80./XJT*.5/TSE
     1NSR)**2
C
C-----------------------------------------------------------------------
C     INCREASE RESIDUAL PHASE VARIANCE AND CCMPUTE THE I-REL.
C-----------------------------------------------------------------------
      D1=D1+PHSERR
C
C-----------------------------------------------------------------------
C     COMPUTE I-REL CF AC TURBULENCE CORRECTED BEAM.
C-----------------------------------------------------------------------
C
      EXD=EXP(-D1)
C
C-----------------------------------------------------------------------
C     IF AO CORRECTED I-REL IS LESS THAN NC AC CORRECTION, ASSUME
C     ONLY TILT CORRECTICN IS USED.
C-----------------------------------------------------------------------
C
      IF (EXD.LT.EXDTST.OR.NFLGSN.EQ.1) GO TO 20
C
      CALL PNDRHO (EXD,RHO,DIA,RHOU,DX,N4,IRRMTF)
C
      GC TO 30
20    CONTINUE
C
C-----------------------------------------------------------------------
C     THIS SETS A FLAG TC PRINT THAT AO SYSTEM IS ONLY TILT
C-----------------------------------------------------------------------
C
      RHC=RHOLD
      NFLGSN=1
C
30    CONTINUE
C
C-----------------------------------------------------------------------
C     ESTABLISH TEST INCREMENTS TO SEE IF FULL ISOPLANATIC CALCULATION
C     NEEDS TO BE DCNE.
C-----------------------------------------------------------------------
C     COMPUTE THE ISCPLANATIC ANGLE.
C-----------------------------------------------------------------------
C
      ISOANG=CCSOMG**(2.6667)*ISOANO
      TSTNEW=NC/ISOANG
      TSTDIF=ABS(TSTNEW**1.666667-TSTCLD)
```

```
      ETSDIP=EXP(TSTDIP)
      IF (NISO.EQ.1) TSIOLD=TSTNEW**1.666667
C
C-----------------------------------------------------------------------
C     DETERMINE IF ISOPLANATIC MTF SHOULD BE RE-COMPUTED
C-----------------------------------------------------------------------
C
      NISO=0
      IF (ETSDIF.GT.1.1) NISO=1
      IF (I.EQ.1) NISO=1
      if (noisc.eq.1) niso=0
40    CONTINUE
C
C-----------------------------------------------------------------------
C     REDUCE PEAK IRRADIANCE BY SLANT DISTANCE
C-----------------------------------------------------------------------
C
      IMAXSC=(RSATD/RANGE)**2
C
C-----------------------------------------------------------------------
C    THIS ALLOWS ONE TO INCLUDE TILT ISOPLANATISM.  NOTE HOWEVER, THAT
C    IF THE FULL ADAPTIVE OPTICS ALGORITHM IS USED WITH THE ISOPLANATISM
C    CORRECTION, THEN THIS CALL SHOULD NOT BE USED-REPEAT-SHOULD NOT BE
C    USED.   ALSO NOTE THAT A VERTICAL TURBULENCE PROFILE IS NEEDED
C    WHEN EVER THIS ROUTINE IS USED.
C-----------------------------------------------------------------------
C
      IF (NFLGSN.EQ.1.AND.NOISO.EQ.0) GO TO 50
      IF (NOISC.EQ.1.OR.NFLAGA.EQ.1) GO TO 60
50    CONTINUE
      OMX=NU
      OMY=0.
      CALL TLTISO (DIA,OMX,OMY,RESTIT,SECOMG,HTRANS,HABVGD)
C
      SIGJIT=SQRT(SGJITC**2+RESTLT)
60    CONTINUE
C
C-----------------------------------------------------------------------
C     COMPUTE IRRADIANCE DECREASE DUE TO AMPLITUDE SCINTILLATION FOR THE
C     OFF ZENITH PASS.  NOTE THAT THIS AS LOSS WILL ONLY BE APPLIED IF
C     FULL ADAPTIVE OPTICS COMPENSATION IS ASSUMED.
C-----------------------------------------------------------------------
C
      CALL SINTLS (TAMP,SIGXZ,SECOMG)
C
C-----------------------------------------------------------------------
C     CALCULATE EFFECTS OF JITTER AND TURBULENCE
C-----------------------------------------------------------------------
C
      SUM=0.
      DX2=DX/2.
C
C-----------------------------------------------------------------------
C     IT IS IMPORTANT TO NOTE THAT ALL THE ARRAYS ARE DEFINED
C     TO BEGIN AT DX/2.
C-----------------------------------------------------------------------
C
      X=DX2
      DO 110 J=1,N4
      IF (X.GT.DIA) GO TO 100
      F1=IRRMTF(J)
      CALL MTFATM (X,DIA,RHO,ADAP,F2)
      F3=JITMTF(J)
      IF (NFLAGA.EQ.1.AND.NFLGSN.EQ.0) GO TO 70
      IF (NOISC.EQ.0) CALL MTFJIT (X,SIGJIT,WAVE,F3)
70    CONTINUE
      F4=1.
      IF (NFLAGA.EQ.0.OR.NOISO.EQ.1.OR.NFLGSN.EQ.1) GO TO 90
      F4=TISO(J)
      IF (NISO.EQ.1) CALL ISOPLA (JJ,NU,X,SECOMG,WAVE,F4,HTRANS,HABVGD,T
     1ISC,N4,J)
90    CONTINUE
      F5=BOMTF(J)
      SUM=SUM+F1*F2*F3*F4*F5*X
100   CONTINUE
      X=X+DX
```

```
110   CONTINUE
      TTURB=SUM*2.*PI*DX
C
C-----------------------------------------------------------------------
C     CALCULATE THE RESULTING INSTENTANEOUS INTENSITY
C-----------------------------------------------------------------------
C     CONVERT TO AN APPROCH WHICH AVERAGES THE RESULT OF AN RSS
C     TREATMENT OF THERMAL BLOOMING WITH A MULTIPLICATIVE TREATMENT
C-----------------------------------------------------------------------
C
      SSQT=1./TTURB-1.
      SSQB=1./TBLOOM-1.
      SSQ=SSQT+SSQB
      TMULT=TTURB*TBLOOM
      TRSS=1./(1.+SSQ)
      CALL BELTCT (TTOTAL,TRSS,TMULT)
      PMAX=PMAXO*TABS*TSCAT*TMAXSC*TTOTAL
C
C-----------------------------------------------------------------------
C     APPLY AVERAGING FACTOR
C     APPROPRIATE TO SPOT SIZE DESIRED
C-----------------------------------------------------------------------
C
      PMAX=PMAX*AVGSPT
C
C
C-----------------------------------------------------------------------
C     IF FULL AO IS USED, DECREASE IRRADIANCE FOR AMPLITUDE
C     SCINTILLATION EFFECTS
C-----------------------------------------------------------------------
C
      TAMPL=1.0
      IF (NFLAGA.EQ.1.AND.NFLGSN.EQ.0) TAMPL=TAMP
      IF (TAMPL.LT.0.5) TAMPL=0.5
      PMAX=PMAX*TAMPL
C
C-----------------------------------------------------------------------
C     ACCUMULATED FLUX
C-----------------------------------------------------------------------
C
      FLUX=FLUX+PMAX*DTIME
C
C-----------------------------------------------------------------------
C     COMPUTE INTEGRATED TIMES AND ACCUMULATED ANGLES. THE IRRADIANCE
C     FUNCTION HAS BEEN EVALUATED AT INTERVAL MID-POINTS.
C-----------------------------------------------------------------------
C
      ECANGF=(TIME+DTIME)/2.*THETDT
      XOF=RS*SIN(ECANGF)
      ZOF=RS*COS(ECANGF)
      XF=XOF
      YF=LY*COS(ANGOFF)+(ZOF-R+LZ)*SIN(ANGOFF)
      ZF=-LY*SIN(ANGOFF)+(ZOF-R+LZ)*COS(ANGOFF)
      RANGEF=SQRT(XF**2+YF**2+ZF**2)
C
      OMEGAF=ARCOS(ZF/RANGEF)
C
C-----------------------------------------------------------------------
C     TIME OF ILLUMINATION FROM ZENITH TO THETA. THIS IS ALSO
C     EVALUATED AT THE LOWER LIMIT AND NOT THE MID-POINT.
C     IF THE COMPUTATIONS ARE DONE FROM THE THETMX TO ZENITH INSTEAD
C     OF THE WAY THEY ARE, THE TIME DEFINITION NEEDS TO BE CHANGED.
C-----------------------------------------------------------------------
C
      TILLUM=TIME/2.+DTIME/2.
C
C============== LOOP RESULTS STORAGE SECTOR ============================C
C
      A(I,1)=I
      A(I,2)=RANGE*XKM
      A(I,3)=PRIDOT/XKM
      A(I,4)=OMEGAF*RTD
      A(I,5)=TILLUM
      A(I,6)=TSCAT
      A(I,7)=TABS
      A(I,8)=REC*XCM
```

```
      A(I,9)=TTURB
      A(I,10)=TAMPL
      A(I,11)=TELOCM
      A(I,12)=TMAXSC
      A(I,13)=PMAX*XK2
      A(I,14)=FLUX*XK2
120   CONTINUE
C
C============== FINAL RESULTS OUTPUT SECTOR ===========================C
C
      B(1)=DIA*XCM
      B(2)=WAVE*XMW
      B(3)=PTOTAL/XMW
      B(4)=TDFIMT
      B(5)=HTRANS
      B(6)=HSAT*XKW
      B(7)=THETMX*RTD
      B(8)=LOFF*XKW
      B(9)=RHOO*XCM
      B(10)=V0
      B(11)=BGEND
      B(12)=THSEE
C
C
      WRITE (6,220)
      WRITE (6,240)  ((A(I,J),J=1,8),I=1,N1)
      WRITE (6,230)
      WRITE (6,250)  (A(I,1),(A(I,J),J=9,14),I=1,N1)
      WRITE (6,330)  (B(II),LL=1,12)
      WRITE (6,130)  ACBICM,AVGSPT
C
      DIA=DIA*XCM
      DIAOBS=DIAOBS*XCM
      BEAMSZ=BEAMSZ*XCM
      WRITE (6,140) DIA,DIAOBS,BEAMSZ
C
      SCALBQ=SCALBQ*XCM
      WRITE (6,150) WAVEBQ,SCALBQ
      B(1)=ABSICZ
      B(2)=XJT
      B(3)=BWIDTH
      B(4)=NA
      WRITE (6,380)  (B(II),LL=1,4)
      WRITE (6,260)
      IF (NFLAGA.EQ.0.AND.NOISO.EQ.1) WRITE (6,310)
      IF (NFLAGA.EQ.1.AND.NOISO.EQ.0) WRITE (6,280)
      IF (NFLAGA.EQ.1.AND.NOISO.EQ.1) WRITE (6,290)
      IF (NFLAGA.EQ.0.AND.NOISO.EQ.0) WRITE (6,300)
      WRITE (6,340) N1,N2,N3,N4,N5
C
      ESIGXZ=EXP(-SIGXZ)
      WRITE (6,160) SIGXZ,ESIGXZ
C
      ZENNU=ZENNU*XMW
      WRITE (6,320) ZENNU
C
      RESTLT=SQRT(RESILT)*XMW
      WRITE (6,360) RESTLT
C
      SGJITO=SGJITO*XMW
      WRITE (6,350) SGJITC,ADAP
C
      FLUX=FLUX*XK2*2.
      TILLUM=TILLUM*2.
      WRITE (6,370) FLUX,TILLUM
      IF (NFLGSN.EQ.1) WRITE (6,170)
      STOP
C
C================== I/O FORMAT STATEMENTS ==================================C
C
500   FORMAT (50X,F20.0)
510   FORMAT (50A1,E20.0)
520   FORMAT (50A1,I20)
530   FORMAT (80A1)
C
130   FORMAT(10X,'BLOCKING ADAPTIVE OPTICS FACTOR  = ',E10.4,/,
```

```
     1      10X,'IRRADIANCE AREA AVERAGING FACTOR = ',E10.4,/)
140   FORMAT(10X,'TELESCOPE DIMENSIONS:',/,
     1      10X,'OUTER DIAMETER          = ',F10.2,' CM',/,
     1      10X,'INNER DIAMETER          = ',F10.2,' CM',/,
     1      10X,'GAUSSIAN WAIST DIAMETER = ',F10.2,' CM',/)
150   FORMAT(10X,'RMS WAVES DISTORTION        = ',E10.4,/,
     1      10X,'PHASE CORRELTATION LENGTH = ',E10.4,' CM',/)
160   FORMAT (10X,'ZENITH LOG AMPLITUDE VARIANCE =',E12.4,/,10X,'RELA',
     1      'TIVE IRRADIANCE REDUCTION =',E12.4,/)
170   FORMAT (10X,'NOTE========THE ADAPTIVE OPTICS SYSTEM USED WILL ',
     1  'PROVIDE DEGRADED PERFORMANCE OVER THE TILT ONLY CASE',/)
180   FORMAT (10X,50A1,F20.6)
185   FORMAT (10X,50A1,I20)
190   FORMAT (1H1,9X,'INPUT DATA FILE:',//)
195   FORMAT (10X,80A1,/)
220   FORMAT(1H1,9X,'PATH ANALYSIS RESULTS:',//,
     1      6X,'STEP',10X,'RANGE',9X,'SLEW',6X,'OMEGA',7X,'TIME',
     1      5X,'ATMOS. TRANSMISSION',10X,'RHO',/,
     1      7X,'NO.',11X,'(KM)',5X,'(MRAD/SEC)',4X,'(DEG)',
     1      6X,'(SEC)',8X,'SCAT',6X,'ABSORP',9X,'(CM)',//)
230   FORMAT(1H1,9X,'TRANSMISSION ANALYSIS OUTPUT:',//,
     1     16X,'TRANSMISSION COEFFICIENTS',13X,'RANGE',6X,'MAX IRRAD',
     1      11X,'FLUENCE',/,
     1      4X,'STEP',5X,'DUE TO',5X,'AMP LOSS',4X,
     1      'THERMAL ',4X,'SCALE',5X,'(KW/CM2)',5X,
     1      '(KJ/CM2)',/,10X,'SPREADING',6X,'WITH AO',5X,'BLOOMING',//)
240   FORMAT(7X,F3.0,5X,F10.3,5X,F8.4,5X,F6.2,5X,F6.2,5X,
     1      F7.5,5X,F7.5,5X,F8.1,/)
250   FORMAT(7X,F3.0,5X,F10.5,5X,F10.5,5X,F10.5,5X,F10.4,5X,E10.4,
     1      5X,E10.4,/)
260   FORMAT (10X,'THIS RUN -')
270   FORMAT (12X,'INCLUDES THE STATISTICAL CLOUD MODEL')
280   FORMAT (12X,'INCLUDES THE FULL ZONAL AO MODEL WITH AN ',
     1      'ISOPLANATISM MODEL')
290   FORMAT (12X,'INCLUDES THE FULL ZONAL AO MODEL WITHOUT AN ',
     1      'ISOPLANATISM MODEL')
300   FORMAT (12X,'INCLUDES FULL TILT CORRECTION WITH TILT ',
     1      'ISOPLANATISM')
310   FORMAT (12X,'IS THE BASIC CODE WITH ONLY SOME MEASURE OF ',
     1      'TILT CORRECTION',/,12X,'AND WITHOUT AN ISOPLANATIC',
     2      ' MODEL',/)
320   FORMAT (10X,'ZENITH LOOK-AHEAD ANGLE        = ',E10.4,' URAD',/)
330   FORMAT(1H1,9X,'CASE DATA AND CALCULATED FACTORS:',//,
     1      10X,'TRANSMITTER DIAMETER      = ',F10.2,' CM',/,
     1      10X,'CAVITY WAVELENGTH         = ',F10.6,' UM',/,
     1      10X,'APERTURE TOTAL POWER      = ',F10.4,' MW',/,
     1      10X,'TIMES DIFFRACTION LIMIT   = ',F10.2,/,
     1      10X,'(WIDE ANGLE SCATTERING)',/,
     1      10X,'TRANSMITTER ALTITUDE      = ',F10.2,' M',/,
     1      10X,'SATELLITE ALTITUDE        = ',F10.2,' KM',/,
     1      10X,'MAX ZENITH ANGLE          = ',F10.2,' DEG',/,
     1      10X,'FLIGHT PATH OFFSET        = ',F10.2,' KM',/,
     1      10X,'RHO0                      = ',E10.4,' CM',/,
     1      10X,'WIND VELOCITY             = ',F10.2,' M/SEC',/,
     1      10X,'HEIGHT OF GROUND          = ',F10.2,' M',/,
     1      10X,'OPT SEEING AT 5500A       = ',E10.2,' ARC-SEC',/)
340   FORMAT(10X,'NUMBER OF INTERVAL STEPS FOR:',/,
     1      12X,'ANGULAR INTERVAL                 = ',I10,/,
     1      12X,'ABSORPTION INTEGRATION           = ',I10,/,
     1      12X,'RHO CALCULATION                  = ',I10,/,
     1      12X,'MTF CALCULATION                  = ',I10,/,
     1      12X,'THERMAL BLOOMING                 = ',I10,/)
350   FORMAT(10X,'2-SIGMA-P BEAM JITTER           = ',F10.2,' URAD',/,
     1      10X,'TURBULENCE JITTER REJECTION     = ',E10.4,/,
     1      10X,'(RESIDUAL = INITAL * ADAP)',/)
360   FORMAT(10X,'ISOPLANATIC JITTER (2-SIGMA-P) = ',E10.4,/)
370   FORMAT(///,10X,'======== PROPAGATION RESULTS ========',//,
     1      10X,'INTEGRATED FLUX ON TARGET       = ',F15.6,' KJ/CM2',/,
     1      10X,'TOTAL ILLUMINATION TIME         = ',F15.2,' SEC')
380   FORMAT(10X,'FOR THE FULL ZONAL A-O MODEL:',/,
     1      12X,'ZENITH TRANS. AT A-O SENSOR   = ',E10.4,/,
     1      12X,'TARGET RADIANT INTENSITY      = ',E10.4,' W/STER',/,
     1      12X,'ADAPTIVE OPTICS BANDWIDTH     = ',E10.4,' HERTZ',/,
     1      12X,'NUMBER OF ACTUATORS         = ',F10.0,/)
      END
```

```
      SUBROUTINE ALFA (A,Z)
C
C---- CALCULATE THE TOTAL MOLECULAR ABSORPTION
C
      DIMENSION ALT(20),ATA(20)
C
C******    THIS DATA FOR CO 5P9 FROM AFWL INFO, REPORTEDLY BASED ON AN
C******    UPDATE OF THE MCCLATCHY LINE DATA.  THE WAVELENGTH FOR THIS
C******    TRANSITION IS 4.99210 MICRONS.
C******    ATMOSPHERE IS MID-LATITUDE SUMMER, CLEAR DAY.
      DATA ALT/0.0,1.0,2.0,3.0,4.0,5.0,6.0,7.0,8.0,9.0,10.0,12.0,14.0,
     1         16.0,18.0,20.0,25.0,30.0,35.0,40.0/
      DATA ATA/0.356,0.269,0.148,7.28E-02,3.35E-02,1.51E-02,6.88E-03,
     1         3.40E-03,1.61E-03,1.79E-03,3.46E-04,6.50E-04,1.78E-05,
     2         1.06E-05,6.21E-06,3.61E-06,0.0,0.0,0.0,0.0/
      NL=19
      INDX=1
      A=0.
      IF ((Z*3.279).GE.1.E5) RETURN
      H=Z*1.E-3
C
C---- SEARCH FOR THE ALTITUDE INDEX
C
      DO 10 I=1,NL
      IF (H.LT.ALT(I)) GO TO 10
      INDX=I
10    CONTINUE
      R=(H-ALT(INDX))/(ALT(INDX+1)-ALT(INDX))
      A=R*(ATA(INDX+1)-ATA(INDX))+ATA(INDX)
      A=A/1000.
      RETURN
      END
```

```
      SUBROUTINE ALFS (S,Z)
C
C---- CALCULATE THE TOTAL SCATTERING
C
      DIMENSION ALT(20),ATS(20)
C
C******   THIS DATA FOR CO 5P9 FROM AFWL INFO, REPORTEDLY BASED ON AN
C******   UPDATE OF THE MCCLATCHY LINE DATA.  THE WAVELENGTH FOR THIS
C******   TRANSITION IS 4.99210 MICRONS.
C******   ATMOSPHERE IS MID-LATITUDE SUMMER, CLEAR DAY.
      DATA ALT/0.0,1.0,2.0,3.0,4.0,5.0,6.0,7.0,8.0,9.0,10.0,12.0,14.0,
     1         16.0,18.0,20.0,25.0,30.0,35.0,40.0/
      DATA ATS/1.41E-03,9.36E-04,1.09E-04,5.57E-05,4.54E-05,3.50E-05,
     1         2.60E-05,1.79E-05,1.14E-05,4.99E-05,3.64E-05,2.91E-05,
     2         2.62E-05,2.66E-05,2.41E-05,1.89E-05,7.00E-06,1.06E-05,
     3         3.28E-06,1.61E-06/
      NL=19
      S=0.
      IF ((Z*3.279).GE.1.E5) RETURN
      H=Z*1.E-3
      INDX=1
C
C---- SEARCH FOR THE ALTITUDE INDEX
C
      DO 10 I=1,NL
      IF (H.LT.ALT(I)) GO TO 10
      INDX=I
10    CONTINUE
      R=(H-ALT(INDX))/(ALT(INDX+1)-ALT(INDX))
      S=R*(ATS(INDX+1)-ATS(INDX))+ATS(INDX)
      S=S/1000.
      RETURN
      END
```

```
      SUBROUTINE ABSORB (N,HT,T)
C
C---- CALCULATES ZENITH THE TOTAL INTEGRATED MOLECULAR TRANSMISSION
C
      COMMON /ATMO/ HATMO
      DELH=(HATMO-HT)/N
      HEIGHT=HT+DELH/2.
      ALPZ=0.
      DO 10 I=1,N
      CALL ALFA (ALP,HEIGHT)
      ALPZ=ALPZ+ALP
      HEIGHT=HEIGHT+DELH
10    CONTINUE
      ALPZ=ALPZ*DELH
      T=EXP(-ALPZ)
      RETURN
      END
```

```
      SUBROUTINE SCAT (N,HT,T)
C
C---- CALCULATES ZENITH THE TOTAL INTEGRATED SCATTERED TRANSMISSION
C
      COMMON /ATMO/ HATMC
      DELH=(HATMO-HT)/N
      HEIGHT=HT+DELH/2.
      ALPS=0.
      DO 10 I=1,N
      CALL ALPS (ALS,HEIGHT)
      ALPS=ALPS+ALS
      HEIGHT=HEIGHT+DELH
10    CONTINUE
      ALPS=ALPS*DELH
      T=EXP(-ALPS)
      RETURN
      END
```

```
      SUBROUTINE RHOZEN (N,HT,HG,W,RHO)
C
C---- COMPUTES YURAS ZENITH ATMOSPHERIC COHERENCE DIAMETER
C
      COMMON /ATMO/ HATMO
      TPI=4.*ARSIN(1.)
      CK=TPI/W
      CKSQ=CK*CK
      DELH=(HATMO-HT)/FLOAT(N)
      HEIGHT=HG+DELH/2.
      SUM=0.
      DO 10 I=1,N
      CALL CN2H (HEIGHT,CN2)
      SUM=SUM+CN2
      HEIGHT=HEIGHT+DELH
10    CONTINUE
      CN1=SUM*DELH
      DEN=2.91*CKSQ*CN1
      RHO=(6.88/DEN)**(.6)
      RHO=RHO/2.1
      RETURN
      END
```

```
      SUBROUTINE FARFLD (DX2,F,G,ML,N4,HSATD,WAVE,PTOTAL,PMAX0)
C
C---- COMPUTES THE FARFIELD IRRADIANCE OF THE APERTURE DISTRIBUTION
C---- AND THEN COMPUTES THE CORRESPONDING APERTURE MTF
C
      DIMENSION F(ML),G(ML)
      COMMON /ARBFLD/ DIA,DIAOBS,BEAMSZ,U0
      PI2=ARSIN(1.)
      PI=2.*PI2
      TWOPI=2.*PI
      CK=TWOPI/WAVE
      CKR=CK/HSATD
      DIASQ=DIA**2
      DOBSSQ=DIAOBS**2
      RFOCUS=1.2*HSATD*WAVE/SQRT(DIASQ-DOBSSQ)
      FACTOR=4.
      FACTOR=2.5
      FACTOR=5.
      RLIM=FACTOR*RFOCUS
      DX0=(DIA-DIAOBS)/2./ML
      DX1=RLIM/ML
      R1=DX1/2.
      DO 20 I=1,ML
      SUM=0.
      R0=DIAOBS/2.+DX0/2.
      DO 10 J=1,ML
      Z=CKR*R0*R1
      CALL J0 (Z,A)
      CALL FIELD (R0,UR)
      SUM=SUM+A*UR*R0
10    R0=R0+DX0
C        BY DIVIDING BY PTOTAL, THE MTF WILL BE UNITY AT THE ORIGIN.
      F(I)=(SUM*CKR*DX0)**2/PTOTAL
20    R1=R1+DX1
C
C---- COMPUTE PMAX0 ON AXIS
C
      SUM=0.
      R0=DIAOBS/2.+DX0/2.
      DO 30 I=1,ML
      CALL FIELD (R0,UR)
      SUM=SUM+UR*R0
30    R0=R0+DX0
      PMAX0=(SUM*CKR*DX0)**2
C
C---- CNORM- FIXES THE MTF SO THAT THE MTF INTEGRATION PRODUCES AN
C---- IDEL VALUE.
C
      CNORM=(WAVE*HSATD)**2*PMAX0/PTOTAL
C
C---- COMPUTE THE MTF
C
      R2=DX2/2.
      DO 50 I=1,N4
      SUM=0.
      R1=DX1/2.
      DO 40 J=1,ML
      Z=CKR*R1*R2
      CALL J0 (Z,A)
      SUM=SUM+A*F(J)*R1
40    R1=R1+DX1
      G(I)=SUM*TWOPI*DX1/CNORM
50    R2=R2+DX2
      RETURN
      END
```

```
      SUBROUTINE J0 (X,F)
C
C---- COMPUTES THE ZERO ORDER BESSEL FUNCTION.
C
C
C
C     DIMENSION A1(16),A2(11),A3(11),A4(15),A5(11),A6(11)
      REAL*8 A1(16),A2(11),A3(11),A4(15),A5(11),A6(11)
      DATA A1/-1.0D-15,4.1D-14,-1.944D-12,7.6487D-11,-2.679257D-9,7.6081
     1636D-8,-1.7619469C8D-6,3.24603288821D-5,-4.606261662060-4,4.8191800
     269468D-3,-.0348937699411409,.1580671023332097,-.3700949938726 5,.2651
     378613203337,-.008723442352852,.315455942949 78/
      DATA A2/1.0D-15,-5.0D-15,4.3D-14,-4.3D-13,5.168D-12,-7.8641D-11,1.
     1630646D-9,-5.1705945D-8,3.075184788D-6,-5.36522046813D-4,1.9989206
     29869504/
      DATA A3/-1.0D-15,4.0D-15,-3.3D-14,3.01D-13,-3.207D-12,4.2201D-11,-
     17.27192D-10,1.7972457D-8,-7.41449841D-7,6.6385199426D-5,-.031111170
     29210674/
      DATA A4/1.1D-14,-5.78D-13,2.5281D-11,-9.42421D-10,2.949707D-8,-7.6
     117587 81D-7,1.58870 1924D-5,-.000260444389349,.003240270182684,-.029
     217552480 6154,.177709117239728,-.6614439341345 43,1.287994098 85768,-
     31.191801160 54122,1.2967175412 1053/
      DATA A5/-1.0D-15,5.0D-15,-4.7D-14,4.7D-13,-5.705D-12,6.8169D-11,-1
     1.871891D-9,6.177634D-8,-3.98728 43D-6,.00089398983308 6,2.00180608 17
     22003/
      DATA A6/1.0D-15,-5.0D-15,3.6D-14,-3.26D-13,3.515D-12,-4.6864D-11,8
     1.22919D-10,-2.0559781D-8,9.1386152 6D-7,-9.62772354920-5,.09355557 4
     2139071/
C--- ZERO ORDER BESSEL FUNCTION
      N=0
C
      IF (N.EQ.1) GO TO 50
      IF (ABS(X).GT.8.0) GO TO 20
      Y=.0625*X*X-2
      B=0.0
      BP1=0.0
      DO 10 I=1,16
      BP2=BP1
      BP1=B
10    B=Y*BP1-BP2+A1(I)
      F=.5*(B-BP2)
      RETURN
20    Y=256/(X*X)-2
      AB=ABS(X)
      B=0.0
      BP1=0.0
      DO 30 I=1,11
      BP2=BP1
      BP1=B
30    B=Y*BP1-BP2+A2(I)
      P=.5*(B-BP2)
      B=0.0
      BP1=0.0
      DO 40 I=1,11
      BP2=BP1
      BP1=B
40    B=Y*BP1-BP2+A3(I)
      Q=4*(B-BP2)/AB
      Y=AB-.785398163397448
      F=.7978845608028 65*(P*COS(Y)-Q*SIN(Y))/SQRT(AB)
      RETURN
50    IF (ABS(X).GT.8.0) GO TO 70
      Y=.0625*X*X-2
      B=0.0
      BP1=0.0
      DO 60 I=1,15
      BP2=BP1
      BP1=B
60    B=Y*BP1-BP2+A4(I)
      F=.0625*(B-BP2)*X
      RETURN
70    Y=256/(X*X)-2
      AB=ABS(X)
      B=0.0
      BP1=0.0
      DO 80 I=1,11
      BP2=BP1
```

```
      BP1=B
80    B=Y*BP1-BP2+A5(I)
      P=.5*(B-BP2)
      B=0.0
      BP1=0.0
      DO 90 I=1,11
      BP2=BP1
      BP1=B
90    B=Y*BP1-BP2+A6(I)
      Q=4*(B-BP2)/AB
      B=SIGN(1.0,X)
      Y=AB-2.35619449019235
      F=.797884560802865*(P*COS(Y)-Q*SIN(Y))/SQRT(AB)
      F=B*F
      RETURN
      END
```

```
      SUBROUTINE FIELD (R,UR)
C
C---- COMPUTES EXIT APERTURE FIELD DISTRIBUTION.  NOTE IT MUST BE
C---- AXI-SYMETRIC.
C
      COMMON /APRFLD/ DIA,DIAOBS,BEAMSZ,U0
      UR=0.
      D=2.*R
      IF (D.GT.DIA.OR.D.LT.DIAOBS) RETURN
      BMRAD=BEAMSZ/2.
      UR=U0*EXP(-(R/BMRAD)**2)
      RETURN
      END
```

```
      SUBROUTINE UOCST (PT,N)
C
C---- COMPUTES NORMALIZATION CONSTANT GIVING PTOTAL ENERGY IN BEAM
C
      COMMON /ARBFLD/ DIA,DIAOBS,BEAMSZ,U0
      PI=2.*ARSIN(1.)
      RO=DIA/2.
      ROSQ=RO**2
      RI=DIAOBS/2.
      RISQ=RI**2
      DX=ROSQ/N
      CST=PI*DX
      X=DX/2.
      U0=1.
      SUM=0.
      DO 10 I=1,N
      ROOTX=SQRT(X)
      IF (ROOTX.GT.RO.OR.ROOTX.LT.RI) GO TO 10
      CALL FIELD (ROOTX,UR)
      SUM=SUM+UR**2
10    X=X+DX
      TEMP=SUM*CST
      U0=SQRT(PT/TEMP)
      RETURN
      END
```

```
      SUBROUTINE MTFATM (X,D,RHO,ADAP,F)
C
C---- COMPUTES ATMOSPHERIC MTF FUNCTION
C
      XD=X/D
      A1=1.-ADAP
      DRHO=D/RHO
      F=EXP(-XD**(1.6667)*(1.-A1*XD**(.3333))*DRHO**(1.6667))
      RETURN
      END
```

```
      SUBROUTINE MTFJIT (X,SIGJIT,WAVE,F)
C
C---- COMPUTES JITTER MTF FUNCTION
C
      TPI=4.*ARSIN(1.)
      CK=TPI/WAVE
      F=EXP(-(CK*X*SIGJIT)**2/8.)
      RETURN
      END
```

```
      SUBROUTINE MTFBQ (X,F)
C
C---- COMPUTES RANDOM PHASE MTF.  ASSUMES A GAUSSIAN CORRELATION
C---- FUNCTION.
C
      COMMON /BQ/ TDFLMT,VARBQ,WAVEBQ,SCALBQ
      TEMP=1.-EXP(-(X/SCALBQ)**2)
      F=EXP(-VARBQ*TEMP)
      RETURN
      END
```

```
      SUBROUTINE BQIREL (A,N4,DX,REL)
      DIMENSION A(N4)
      SUM=0.
      X=DX/2.
      DO 10 I=1,N4
      CALL MTFEQ (X,F)
      SUM=SUM+A(I)*F*X
      X=X+DX
10    CONTINUE
      REL=SUM*DX*6.2831852
      RETURN
      END
```

```
      SUBROUTINE DETWAV (A,DX,N4)
C
C---- IF THE RMS WAVES OF PHASE DISTORTION ARE NOT SPECIFIED,
C---- THEN THIS ROUTINE WILL DETERMINE THE APPROPRIATE WAVEBQ THAT
C---- PRODUCES THE SPECIFIED TDFLMT.
C
      COMMON /BQ/ TDFLMT,VARBQ,WAVEBQ,SCALEQ
      DIMENSION A(N4)
      RELO=1./TDFLMT**2
      VARBQ=-ALOG(RELO)
      DVBQ=VARBQ/10.
      TEST=.005
      NSIGNO=1.
10    CONTINUE
      CALL BQIREL (A,N4,DX,REL)
      DREL=REL-RELO
      IF (ABS(DREL)/RELO.LT.TEST) GO TO 40
      IF (DREL.LT.0.) GO TO 20
      NSIGN1=1
      GO TO 30
20    NSIGN1=-1
30    CONTINUE
      IF (NSIGN1.NE.NSIGNO) DVBQ=DVBQ/2.
      VARBQ=VARBQ+DVBQ*NSIGN1
      NSIGNO=NSIGN1
      GO TO 10
40    CONTINUE
      TWOPI=6.2831852
      WAVEBQ=SQRT(VARBQ)/TWOPI
      RETURN
      END
```

```
      SUBROUTINE JIT (A,DX,N4,SIGJIT,WAVE)
C
C---- COMPUTES ARRAY FOR JITTER MTF.
C
      DIMENSION A(N4)
      X=DX/2.
      DO 10 I=1,N4
      CALL MTFJIT (X,SIGJIT,WAVE,F)
      A(I)=F
10    X=X+DX
      RETURN
      END
```

```
      SUBROUTINE BM  (A,DX,N4)
C
C-----COMPUTES ARRAY FOR BEAM QUALITY MTF.
C
      DIMENSION A(N4)
      X=DX/2.
      DO 10 I=1,N4
      CALL MTFBQ (X,F)
      A(I)=F
10    X=X+DX
      RETURN
      END
```

```
      SUBROUTINE CN2H (HEIGHT,CN2)
C
C     CACULATE ATMOSPHERIC VERTICAL TURBULENCE
C
C---- HUFNAGELS LATEST MODEL-GOOD ONLY ABOVE 3 KILOMETERS
C
      CN2=2.2*(1.E-5*10.**(-.3)*HEIGHT)**10.*EXP(-HEIGHT/1000.)
      CN2=CN2+1.E-16*EXP(-HEIGHT/1500.)
      CN2=CN2*2.7
C
C---- THIS MODIFICATION IS USED to include turbulence at lower alts
C
      CN2=CN2+1.E-14*EXP(-HEIGHT/100.)
      RETURN
      END
```

```
      SUBROUTINE AV (N,V0,PHIDCT,HT,COSWND,COSOMG,E)
C
C--- COMPUTES THAT PART OF THERMAL BLOOMING THAT CHANGES WITH SLANT PATH
C
      COMMON /ATMO/ HATMO
      COSSQ=COSWND
      DELH=(HATMO-HT)/N
      RG=DELH/2.
      HEIGHT=HT+DELH/2.
      V0COS=V0*COSSQ
      SUM=0.
      SUMAS=0.
      DO 10 I=1,N
      CALL ALFA (ALA,HEIGHT)
      CALL ALFS (ALS,HEIGHT)
      SUMAS=SUMAS+ALS+ALA
      ALOSS=EXP(-SUMAS*DELH/COSOMG)
      SUM=SUM+ALOSS*ALA/(V0COS+RG*PHIDCT)
      RG=RG+DELH
      HEIGHT=HEIGHT+DELH
10    CONTINUE
      SUM=SUM*DELH
      E=SUM**2
      RETURN
      END
```

```
      SUBROUTINE PRIPHS (ML,MLH,WAVE,PH)
C
C----- COMPUTES THAT PART OF THERMAL BLOOMING PHASE THAT DOES NOT DEPEND
C----- ON SLANT RANGE
C
      COMMON /ARBFLD/ DIA,DIAOBS,BEAMSZ,U0
      DIMENSION PH(MLH,ML)
      MLM=ML-1
      MLHM=MLH-1
      DIASQ=DIA**2
      RADSQ=DIASQ/4.
      PI4=ARSIN(1.)/2.
      CK=8.*PI4/WAVE
      SCALE=CK*(2.72E-4*.4)/(1.01E5*1.4)
      RCSQ=(DIA/2.)**2
      RISQ=(DIACBS/2.)**2
      DELN=DIA/MLM
      XI=DELN/2.
      YI=-DIA/2.+DELN/2.
      X=XI
      DO 20 I=1,MLHM
      Y=YI
      SUM=0.
      XSQ=X*X
      DO 10 J=1,MLM
      RSQ=Y*Y+XSQ
      R=SQRT(RSQ)
      FACTOR=0.
      IF (RSQ.LT.RCSQ.AND.RSQ.GT.RISQ) CALL FIELD (R,FACTOR)
      FACTOR=FACTOR**2
      SUM=SUM+FACTOR
      PH(I,J)=SUM*SCALE*DELN
      Y=Y+DELN
10    CONTINUE
      X=X+DELN
20    CONTINUE
      RETURN
      END
```

```
      SUBROUTINE RESEHS (MI,MLH,PH)
C
C---- CALCULATES THE RESIDUAL PHASE AFTER THE MEAN,TILT, AND FOCUS
C---- HAVE BEEN REMOVED.
C
      DIMENSION PH(MLH,ML)
      COMMON /ABBFLD/ DIA,DIAOBS,BEAMSZ,U0
      MLHM=MLH-1
      MLM=ML-1
      DELN=DIA/MLM
      XI=DELN/2.
      YI=-DIA/2.+DELN/2.
      RCSQ=(DIA/2.)**2
      RISQ=(DIAOBS/2.)**2
C
C        COMPUTE NORMALIZATION CONSTANTS
C
      CALL COEFS (A0,A1,A2,A3,A4,MLM,MLHM,DELN)
C
C---- COMPUTE EXPANSION COEFFICIENTS
C
      SUM1=0.
      SUM2=0.
      SUM3=0.
      SUM4=0.
      X=XI
      DO 20 I=1,MLHM
      XSQ=X**2
      Y=YI
      DO 10 J=1,MLM
      YSQ=Y**2
      RSQ=XSQ+YSQ
      IF (RSQ.GT.RCSQ.OR.RSQ.LT.RISQ) GO TO 10
      CALL FIELD (SQRT(RSQ),UR)
C
C---- DETERMINE EXPANSION COEFFICIENTS RELATIVE TO A UNIFORM
C---- WEIGHTING FUNCTION.
C
      FT=0.
      IF (ABS(UR).GT.1.E-2) FT=1.
      FACTOR=PH(I,J)*FT
      SUM1=SUM1+FACTOR*X
      SUM2=SUM2+FACTOR*Y
      SUM3=SUM3+FACTOR*RSQ
      SUM4=SUM4+FACTOR
10    Y=Y+DELN
20    X=X+DELN
C------- ADJUST FOR HALF PLANE INTEGRATION
      SUM1=0.
      SUM2=SUM2*2.
      SUM3=SUM3*2.
      SUM4=SUM4*2.
C
      DELNSQ=DELN**2
      PHMEAN=A0*SUM4*DELNSQ
      PHTLTX=A1*SUM1*DELNSQ
      PHTLTY=A2*SUM2*DELNSQ
      PHFOC=(A3*SUM3+A4*SUM4)*DELNSQ
C
C
C---- SUBTRACT THE MEAN,TILT,AND FOCUS CURVATURES.
C
      X=XI
      DO 40 I=1,MLHM
      XSQ=X**2
      Y=YI
      DO 30 J=1,MLM
      YSQ=Y**2
      RSQ=XSQ+YSQ
      IF (RSQ.GT.RCSQ.OR.RSQ.LT.RISQ) GO TO 30
      PH(I,J)=PH(I,J)-PHTLTX*A1*X-PHTLTY*A2*Y-PHFOC*(A3*RSQ+A4)-PHMEAN*A
     10
30    Y=Y+DELN
40    X=X+DELN
      RETURN
      END
```

```
      SUBROUTINE COEFS (A0,A1,A2,A3,A4,MLM,MLBM,DELN)
C
C---- COMPUTES TILT AND FOCUS NORMALIZTION CONSTANTS
C
      COMMON /ARBFLL/ DIA,DIAOBS,BEAMSZ,UO
      ROSQ=(DIA/2.)**2
      RISQ=(DIAOBS/2.)**2
      DELNSQ=DELN**2
      YI=-DIA/2.+DELN/2.
      XI=DELN/2.
      X=XI
      SUM1=0.
      SUM2=0.
      SUM3=0.
      SUM4=0.
      DO 20 I=1,MLBM
      XSQ=X**2
      Y=YI
      DO 10 J=1,MLM
      YSQ=Y**2
      RSQ=XSQ+YSQ
      RSQSQ=RSQ**2
      IF (RSQ.GT.ROSQ.OR.RSQ.LT.RISQ) GO TO 10
      CALL FIELD (SQRT(RSQ),UR)
C
C-----DETERMINE NORMALIZATION COEFFICIENTS RELATIVE TO A UNIFORM
C-----WEIGHTING FUNCTION.
C
      FT=0.
      IF (ABS(UR).GT.1.E-2) FT=1.
      FACTOR=FT
      SUM1=SUM1+FACTOR
      SUM2=SUM2+FACTOR*XSQ
      SUM3=SUM3+FACTOR*YSQ
      SUM4=SUM4+FACTOR*RSQSQ
10    Y=Y+DELN
20    X=X+DELN
C-------- ADJUST FOR HALF PLANE INTEGRATION
      SUM1=SUM1*2.
      SUM2=SUM2*2.
      SUM3=SUM3*2.
      SUM4=SUM4*2.
C
      A0=SQRT(1./(SUM1*DELNSQ))
      A1=SQRT(1./(SUM2*DELNSQ))
      A2=SQRT(1./(SUM3*DELNSQ))
      B=-SUM1/(SUM2+SUM3)
      A3=SQRT(B*B/((B*B*SUM4-SUM1)*DELNSQ))
      A4=A3/B
C
      RETURN
      END
```

```
      SUBROUTINE PHVAR (ML,MLH,ETOTAL,PH,SIGSQ0)
C
C-----COMPUTES THE THERMAL BLOOMING PHASE VARIANCE
C
C-----VARIANCE IS COMPUTED LIKE THE STREHL RATIO ACCORDING TO THE
C----- FIELD AS A WEIGHTING FUNCTION.
C
      COMMON /ARBFLD/ DIA,DIAOBS,BEAMSZ,U0
      DIMENSION PH(MLH,ML)
      RCSQ=(DIA/2.)**2
      RISQ=(DIAOBS/2.)**2
      MLM=ML-1
      MLHM=MLH-1
      DELN=DIA/MLM
      XI=DELN/2.
      YI=-DIA/2.+XI
      X=XI
      SUM1=0.
      SUM2=0.
      SUM3=0.
      DO 30 I=1,MLHM
      Y=YI
      XSQ=X*X
      DO 20 J=1,MLM
      RSQ=XSQ+Y*Y
      IF (RSQ.GT.RCSQ.OR.RSQ.LT.RISQ) GO TO 10
      CALL FIELD (SQRT(RSQ),UR)
      SUM1=SUM1+UR
      SUM2=SUM2+UR*PH(I,J)**2
      SUM3=SUM3+UR*PH(I,J)
10    CONTINUE
      Y=Y+DELN
20    CONTINUE
      X=X+DELN
30    CONTINUE
C-------- ADJUST FOR HALF PLANE INTEGRATION
      SUM1=SUM1+2.*DELN**2
      SUM2=SUM2+2.*DELN**2
      SUM3=SUM3+2.*DELN**2
C
C        NORMALIZE WITH RESPECT TO INTEGRAL OF THE FIELD.
C
      SIGSQ0=SUM2/SUM1-(SUM3/SUM1)**2
C
      RETURN
      END
```

```
      SUBROUTINE ISOTHB (N,HT,HG,W,ISOANG)
C
C---- COMPUTE ZENITH ISOPLANATIC ANGLE BASED UPON D.L. FRIEDS
C-----DEFINITION
C
      COMMON /ATMO/ HATMO
      REAL ISOANG
      TPI=4.*ARSIN(1.)
      CK=TPI/W
      CKSQ=CK*CK
      DELH=(HATMO-HT)/N
      HEIGHT=HG+DELH/2.
      DHT=DELH/2.
      SUM=0.
      DO 10 I=1,N
      CALL CN2H (HEIGHT,CN2)
      SUM=SUM+CN2*DHT**1.66666667
      HEIGHT=HEIGHT+DELH
      DHT=DHT+DELH
10    CONTINUE
      CNI=SUM*DELH
      DEN=2.91*CKSQ*CNI
      ISOANG=(6.88/DEN)**.6*.314
      RETURN
      END
```

```
      SUBROUTINE ISOPLA (JJ,XNU,R,SECOMG,WAVE,XINT,HT,HG,TISO,N4,II)
C
C-----THIS SUBROUTINE COMPUTES THE ISOPLANATIC MTF FOR A FULL AO
C-----COMPENSATED SYSTEM DEVELOPED BY DL FRIED
C
      DIMENSION H(23),C(19),C2(19),C4(19)
      DIMENSION TISO(N4)
      DIMENSION S(19),XMU(20),CN2(23)
      COMMON /ATMO/ HATMO
      IF (JJ.GE.1) GO TO 30
      NH=20
      N=18
      DELH=(HATMO-HT)/NH
      HEIGHT=HG+DELH/2.
      DO 10 K=1,NH
      CALL CN2H (HEIGHT,CNSQ)
      CN2(K)=CNSQ
      H(K)=HEIGHT
10    HEIGHT=HEIGHT+DELH
      PI=3.1415926
      A13=1./3.
      A56=5./6.
      A572=5./72.
      A143=14./3.
      A9127=91./27.
      A73=7./3.
      A53=5./3.
      A12=1./2.
      DPHI=PI/2./N
      PHI=DPHI/2.
      DO 20 J=1,N
      C(J)=COS(PHI)
      PHI=PHI+DPHI
      C2(J)=C(J)*C(J)
20    C4(J)=C2(J)*C2(J)
30    CONTINUE
      JJ=JJ+1
      XA=XNU*SECOMG/R
      DO 40 J=1,N
40    S(J)=0.
      DO 110 K=1,NH
      X=H(K)*XA
      XX=CN2(K)
      IF (X.LT.0.1) GO TO 60
      IF (X.GT.10.) GO TO 80
      X2=X*X
      DO 50 J=1,N
      F=1.+X**A53-A12*(1.+2.*X*C(J)+X2)**A56-A12*(1.-2.*X*C(J)+X2)**A56
50    S(J)=S(J)+F*XX
      GO TO 100
60    X53=X**A53
      X2=X*X
      X4=X2*X2
      DO 70 J=1,N
      F=X53-A56*X2*(1.-A13*C2(J))+A572*X4*(1.-A143*C2(J)+A9127*C4(J))
70    S(J)=S(J)+F*XX
      GO TO 100
80    X13=X**(-A13)
      X73=X13/(X*X)
      DO 90 J=1,N
      F=1.-A56*X13*(1.-A13*C2(J))+A572*X73*(1.-A143*C2(J)+A9127*C4(J))
90    S(J)=S(J)+F*XX
100   CONTINUE
110   CONTINUE
      XMU(1)=1./XA
      DO 120 J=1,N
120   XMU(J+1)=114.88*DELH*S(J)
C
C       NOW INTEGRATE OVER PHI
C
      CST=R**A53*SECOMG/WAVE**2
      SUM=0.
      DO 130 I=1,N
130   SUM=SUM+EXP(-XMU(I+1)*CST)
C
C
```

```
C
      XINT=SUM*DPHI*2./PI
      TISO(II)=XINT
      RETURN
      END
```

```
      SUBROUTINE FNDREC (EXD,RHO,DIA,RHOU,DX,N4,IRRMTF)
C
C---- THIS SUBROUTINE DETERMINES WHAT VALUE OF RHO WOULD PRODUCE THE AC
C---- CORRECTED STREHL AS IF THERE WERE NO COMPENSATION AT ALL
C
      REAL IRRMTF(N4)
C
      R=RHOU
      DR=RHOU/2.
      NSIGNO=-1
      NSIGN=-1
10    CONTINUE
      CALL TRBREL (IRRMTF,DIA,N4,DX,SR,R)
      IF (ABS(SR-EXD)/EXD.LT..1) GO TO 40
      DIF=SR-EXD
      IF (DIF.LT.0.) GO TO 20
      NSIGN=1
      GO TO 30
20    NSIGN=-1
30    CONTINUE
      IF (DIF.GE.0.) DR=DR/2
      NSIGNO=NSIGN
      R=R-DR*NSIGN
      GO TO 10
40    CONTINUE
      RHO=R
      RETURN
      END
```

```
      SUBBOUTINE TBERFL (IRRMTF,DIA,N4,DX,TREL,RHO)
C
C---- THIS SUBBOUTINE COMPUTES THE RELATIVE INTENSITY DUE TO A TOTAL
C-----TILT OBRRECTED SYSTEM FOR TURBULENCE ONLY.
C
      REAL IRRMTF(N4)
      PI=2.*ARSIN(1.)
      SUM=0.
      DX2=DX/2.
      X=DX2
      DO 10 I=1,N4
      F1=IRRMTF(I)
      CALL MTFATM (X,DIA,RHO,0.,F2)
      SUM=SUM+F1*F2*X
      X=X+DX
10    CONTINUE
      TREL=SUM*2.*PI*DX
      RETURN
      END
```

```
      SUBROUTINE TLTISC (D,OMX,OMY,RESTLT,SECOMG,HTRANS,HABVGD)
C
C-----THIS SUBROUTINE COMPUTES THE RESIDUAL TILT DUE TO ISOPLANATISM
C
      COMMON /ATMO/ HATMO
      N=100
      E56=5./6.
      E53=5./3.
      DS=(HATMO-HTRANS)/N
      H=HABVGD+DS/2
      SUM=0.
C
      DO 10 I=1,N
C
      CALL CN2H (H,CN2)
C
      Z=SECOMG*H
C
      ARG1=((D+Z*OMX)**2+(Z*OMY)**2)**E56
      ARG2=((D-Z*OMX)**2+(Z*OMY)**2)**E56
      ARG3=(Z**2*(OMX**2+OMY**2))**E56
      ARG4=D**E53
      ARG5=((Z*OMX)**2+(D-Z*OMY)**2)**E56
      ARG6=((Z*OMX)**2+(D+Z*OMY)**2)**E56
C
      SUM=SUM+(4.*ARG4+4.*ARG3-ARG2-ARG5-ARG1-ARG6)*CN2
      H=H+DS
 10   CONTINUE
C
C---- THIS IS THE RESULTANT 2-SIGMA-R TILT DUE TO ISOPLANATISM.
C
      RESTLT=SUM*DS*SECOMG*2.91/D**2*2.
C
      RETURN
      END
```

```
      SUBROUTINE RELTCT (T,TR,TM)
C
C----- WE HAVE FOUND THE DETAILED MTF CODE TO GIVE RESULTS
C------ WHICH LIE BETWEEN AN RSS MODEL FOR BLOOMING AND A
C------ MULTIPLICATIVE APPROACH.  THIS SUBROUTINE IS AN ATTEMPT
C------ AT BETTER MATCHING THE RESULTS OF THE MTF CODE BY
C------ AVERAGING THE RSS AND THE MULTIPLICATIVE RESULTS.
C
C
      T=(TR+TM)/2.
      RETURN
      END
```

```
      SUBROUTINE BLOCM (D,B,S,T)
C
C-----THESE BLOCKING IRBL MODELS ARE CURVE FITTED TO GUTSMTF
C-----RUNS FOR SIGSQ'S GREATER THAN ABOUT 1.2. THE APERTURE
C-----DISTRIBUTIONS USED HAD OBSCURATIONS OF .1 X THE OUTER
C-----DIAMETER.  IF BETTER IS REQUIRED, RECOMMEND BASELINING
C-----TO THE GUTSMTF CODE AGAIN.

      SQRTS=SQRT(S)
      TRG=-.08705+SQRTS*2.91485+.1723*S
      TRG=1./TRG
      TRU=1.2877-SQRTS*2.6491+4.09603*S
      TRU=1./TRU
      T=(1.-(D/B)**2)*TRU+(D/B)**2*TRG
      IF (D.GT.B) T=TRG
      RETURN
      END
```

```
      SUBROUTINE SCINT (SIGXZ,N,HTRANS,HGRND,WAVE)
C
C---- THIS ROUTINE COMPUTES THE VARIANCE OF THE LOG AMPLITUDE
C---- FOR A ZENITH ANGLE.  THE RESULTS WILL ONLY BE USED
C---- IN THE EVENT THAT FULL AO IS UTILIZED IN THE RUN.
C
      COMMON /ATMO/ HATMO
      CK=6.28/WAVE
      HTOTAL=HATMO-HTRANS
      DH=HTOTAL/N
      H=HTRANS+DH/2.
      C56=5./6.
      SUM=0.
      DO 10 I=1,N
      H56=H**C56
      CALL CN2E (H,CN2)
      SUM=SUM+CN2*H56
      H=H+DH
10    CONTINUE
      CK76=CK**(7./6.)*DH*0.56
      SIGXZ=SUM*CK76
      RETURN
      END
```

```
      SUBROUTINE SINTIS (TAMP,SIGXZ,SECOMG)
C
C---- COMPUTE THE LOG AMPLITUDE SCINTILLATION VARIANCE
C---- FOR OFF-ZENITH CONDITIONS AND THE RELATIVE IRRADIANCE
C---- REDUCTION WHEN FULL AO IS USED.
C
      TAMP=EXP(-SIGXZ*SECOMG**(11./6.))
      RETURN
      END
```

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